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LUNAR ARTICULATED REMOTE TRANSPORTATION SYSTEM

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FAMU/FSU College of Engineering, Tallahassee, Florida

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Abstract

The students of the FAMU/FSU College of Engineering continued their design from 1988-1989 on a first generation lunar transportation vehicle for use on the surface of the moon between the years 2010 and 2020. Attention is focussed on specific design details on all components of the Lunar Articulated Remote Transportation System (Lunar ARTS). The Lunar ARTS will be a three cart, six wheeled articulated vehicle. It s purpose will be for the transportation of astronauts and/or materials for excavation purposes at a short distance from the base (37.5 kilometers).

The power system includes fuel cells for both the primary system and the back-up system. The vehicle has the option of being operated in a manned or unmanned mode. The unmanned mode includes stereo imaging with signal processing for navigation. For manned missions the display console is a digital readout displayed on the inside of the astronaut's helmet. A microprocessor is also on board the vehicle. Other components of the vehicle include: a double wishbone/flexible hemispherical wheel suspension; chassis; a steering system; motors; seat restraints; heat rejection systems; solar flare protection; dust protection; and meteoroid protection. A one-quarter scale dynamic model has been built to study the dynamic behavior of the vehicle. The dynamic model closely captures the mechanical and electrical details of the total design.

Acknowledgements

The FAMU/FSU College of Engineering would like to take this opportunity to express our thanks and gratitude to those persons and organizations which have helped to produce this paper.

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1. Main Overview

1.1 Introduction

It is inevitable that man will extend beyond the earth's boundaries and into space. Permanent habitation of the moon is the first step towards future exploration. First generation exploration (year 2010-2020) will include a base inhabited by approximately 15 astronauts (scientists, engineers, and doctors) whose purpose will be to explore the lunar surface and begin the building of permanent bases for lunar colony habitation. It will be necessary for the astronauts to have reliable transportation system during their lunar stay whose operation is independent on the time of day it is being used (except in the case of solar flare activity). This transportation system must be able to provide adequate transportation for two astronaut for a maximum excursion time of 10 hours. There must also be the capability of carrying additional payload such as additional men or large amounts of lunar regolith. The Lunar Articulated Remote Transportation System (Lunar ARTS or LARTS) is designed for this purpose (Figure 1.1).

This vehicle consists of three carts. The first cart carries the astronauts, the navigation equipment, the cameras, directional lighting and backup communication system hardware. The second cart houses the power system, the solar flare protection blanket, and the heat rejection system for the power system. The third cart will be used for carrying cargo or for two additional astronauts. The vehicle will also have the capability of being operated in an unmanned mode. Using the concept of articulation and detachable hitches, the vehicle will be able to operate with either two carts or three carts. The first two carts will be permanently hitched together while the second and third cart will be joined together with a flexible, removable hitch which will allow the astronauts to detach the third cart.

1.2 Previous Work

Previous work had been completed on the power system, suspension design and wheels by the 1988 – 1989 FAMU/FSU senior aerospace design group [1]. The original power system was designed for a much larger power than the Lunar ARTS required so the power system was redesigned. The suspension system was designed to be a double wishbone. Because the mass of the vehicle had changed the Dynamic Analysis Design Software (DADS) analysis was run again to fit the revised conditions of this year's vehicle. The wheel geometry remains the same as previously designed, but fins were added for structural support and possibly lower the amount of material needed for the spherical shell. The number of carts proposed has been changed from four to three (four carts have been proven to be unstable).

1.3 Project Management

Eight mechanical and two electrical engineering students participated in the design work of this vehicle during the 1989 – 1990 school year. At the beginning of the project term, the students determined that the vehicle could be described by breaking it down into 6 system areas. These include: requirements, power, mobility, navigation, EVA/crew stations, and heat rejection/protection. All components on this vehicle can be placed under one of these systems. Figure 1.2 shows the breakdown of the Lunar ARTS vehicle according to its systems and their components. The final deliverable to the faculty was a report with complete analysis on every component of the Lunar ARTS vehicle and a one quarter scale prototype model of the Lunar ARTS vehicle.

A Gantt chart (as shown in appendix A.1) was completed to show timeline and student responsibilities for all components on the vehicle. A critical timeline was marked out and design analysis on all of the components of the vehicle was started. Weekly meeting were held with the ten design students and 2 professors. An agenda was handed to each student participating in the deign project two days prior to each weekly meeting. This enabled the student time to adequately prepare for each meeting as well as serve as a reminder to each of the student regarding his/her responsibilities. In order to charter the progress of our work status reports were given by all students on each of their projects during the weekly meetings. Integration and interface issues were also

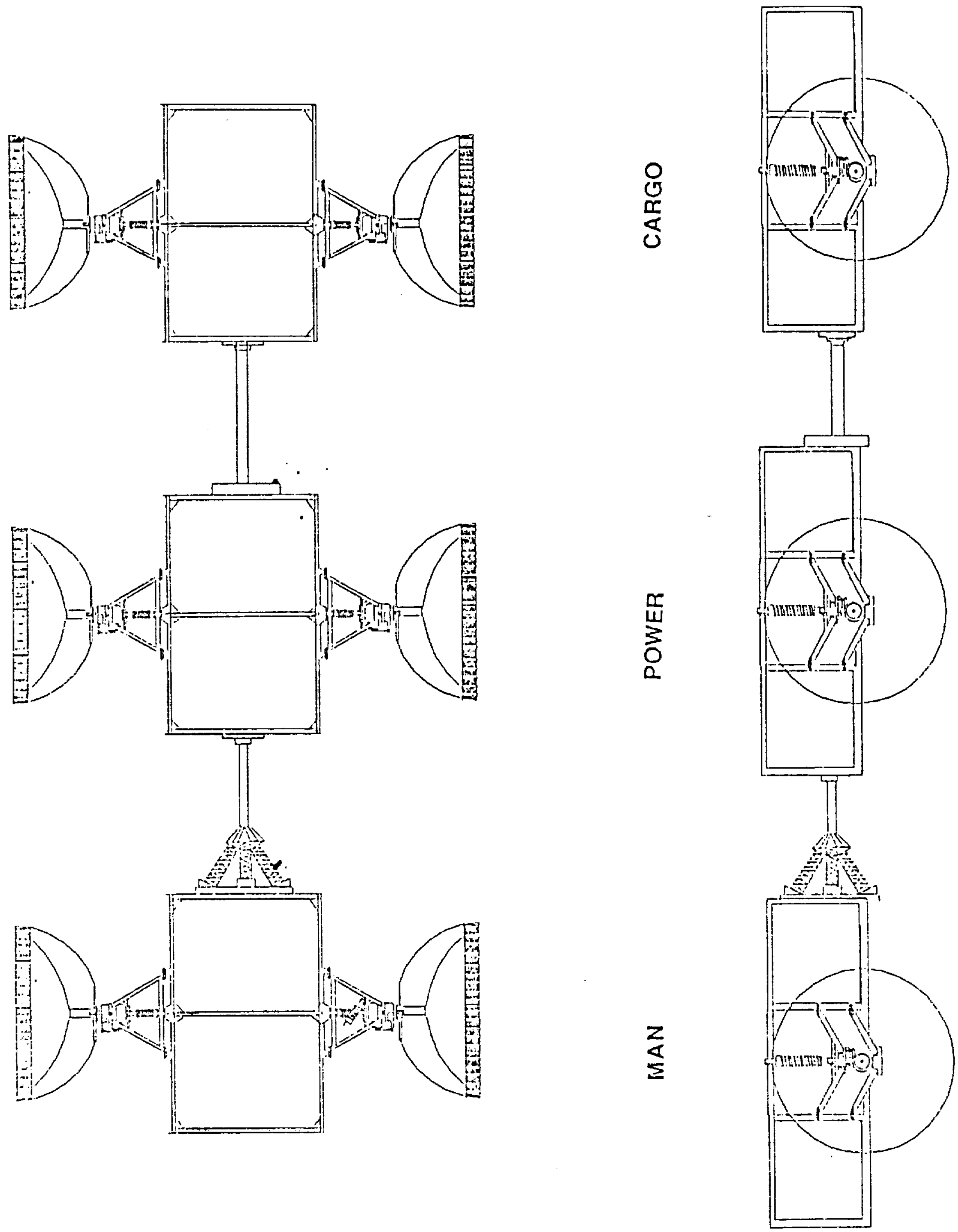

Figure 1.1. Lunar Articulated Remote Transportation System.

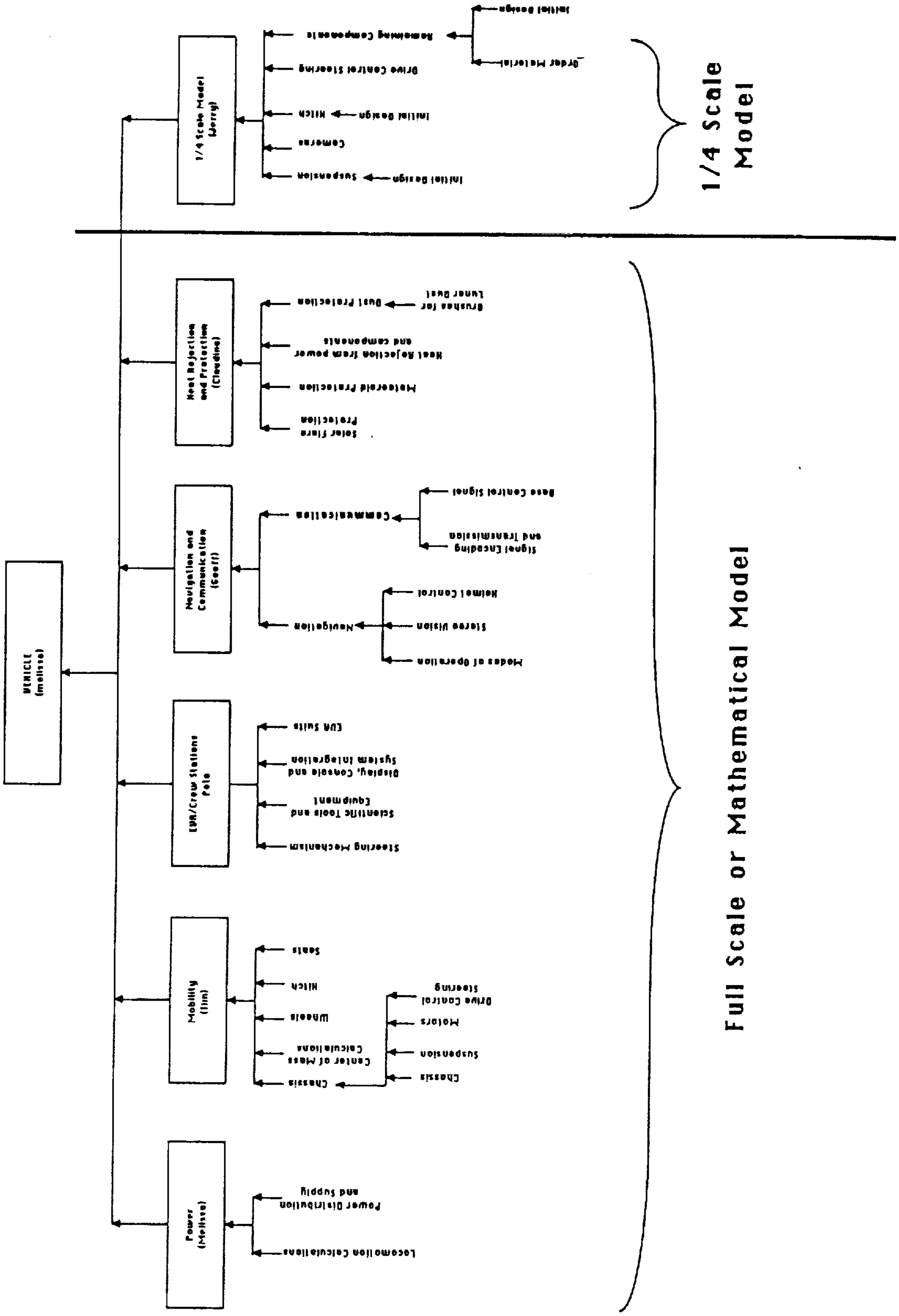

Figure 1.2. System breakdown of the Lunar ARTS.

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addressed during these weekly meetings. Several subcritical design reviews were performed within the student group throughout the semester on all components no later than two weeks after a component completion date. Interim critical design reviews were accomplished by giving oral presentations twice a semester to the faculty. Finally, a formal design reviews on the entire vehicle and the prototype model was completed on April 13, 1990. Appendix A.1 shows a breakdown of the second semester timeline for the project.

2. Design Requirements for the Lunar ARTS

2.1 Introduction

The design constraints for the Lunar Articulated Remote Transportation System include operation, performance, and configuration requirements. The design requirements were set in accordance with the purpose of the Lunar ARTS vehicle, which is to transport men and material on the moon between the years 2005 and 2015.

2.2 Operation Requirements

1. This vehicle will be in operation between the years 2005 and 2015.
2. Design criteria for the vehicle include the following:
   a. Reliability and simplicity
   b. Maximum payload capacity of 750 kg.
   c. Ease of operation
   d. Maintainability
   e. Mobility
3. The vehicle is assumed to operate in recent lunar sites of interest characterized by data from previous landings. Two of the four sites lie on flat mare surfaces surrounded by mountains (Lacus Veris and Taurus Littrov), one lies purely in flat mare (Nubium), and one is a rugged highlands region (South Pole.)

2.3 Performance Requirements

1. The vehicle will perform missions of 60 km (30 km radius from base) with men and 75.0 km (37.5 km radius from base) without men per day. There is a maximum of 10 hours per mission (this includes Extra Vehicular Activity (EVA) time). The vehicle will travel with speeds up to 10 km/hr on 0° slope.
2. The maximum slope angle is 30° while fully loaded.
3. The vehicle will provide controllable forward (0 - 10 km/hr) and reverse continuously variable speed.
4. The vehicle will provide a maximum steering turn radius of 30°.
5. There will be at least 3 displays which show total distance traveled for a mission, total mileage of vehicle, and a variable control travel display with the capability to reset the display of distance traveled to 0. There will also be time displays which include total mission time, and a variable time with the capability of being reset to 0.
6. There will be three-dimensional vision capability for the navigation system. Two-dimensions will be incorporated by stereo vision and the third dimension will use a laser range finder.
7. Protection must be provided to the astronauts for the following:
   a. Dust accumulation

b. Solar reflection off Lunar ARTS surfaces

c. Solar flare protection

8. Design of the Lunar ARTS shall include the following safety features:

   a. No sharp protuberances

   b. A restraint system to prevent astronauts from being ejected from the vehicle.

   c. Provide adequate handholds for ride stability.

   d. Comfort

   e. No hot electrical components should be in contact with astronauts.

   f. Back-up system will be used so that no single failure of a component will endanger crew or will cause an inoperable vehicle.

9. When Lunar ARTS is brought back to lunar base, the dust will be removed.

10. The vehicle will provide materials for drilling and storage.

2.4 Configuration Requirements

1. Each wheel will have the following characteristics: elastic, solid wheels; rigid or semi-rigid chassis.
2. Maximum mass: 2700 kg loaded; 1480 kg unloaded
3. Minimize operation impedance due to dust.
4. Structural system factor of safety is 1.5.
5. Provide storage space, protection, and means of attaching on the Lunar ARTS tools for lunar operation.
6. House and protect cable and wiring.
7. Each wheel will must have a separate driving motor.
8. Provide display and control console.
9. Structure should be optimized for lowest weight.
10. Provide accommodations for two astronauts with EVA suits and a payload of 750 kg. Payload can include either lunar regolith or two additional astronauts with EVA suits.
11. Power source will be no more than 25% of the vehicle weight. This includes back-up power system for locomotion and communication as well as the heat rejection systems for the vehicle.
12. Astronauts traveling on the vehicle will have a switch on the vehicle to over-ride automated control of vehicle.
13. Provide thermal and micrometeoroid protection.
14. Provide device to remove lunar dust and debris from Lunar ARTS while away from base.
15. Provide shock absorbers.
16. The chassis of each cart shall not exceed the overall dimensions of a length of 2.73 meters (9 feet), a width of 1.83 meters (6 feet) and a depth of 1.37 meters (4 .5 feet).

2.5 Individual Component Masses

A mass breakdown of the vehicle according to each cart and its components can be found in appendix A.2.

3. Power

3.1 Introduction

The first analysis to be performed on the vehicle is the power system. This is extremely important, as all other systems' designs are dependent upon the power system. In deciding on a power system for the Lunar ARTS, it was necessary to calculate the power that was required for locomotion as well as the other components on the vehicle. This was done using two programs. The first program (section 3.3.1) is to calculate the amount of power needed for locomotion when the vehicle is operating fully loaded. Wheel condition had to be specified in order to calculate the locomotion energy of the vehicle. The value obtained for locomotion was then entered into the power program (section 3.3.2) in conjunction with all other components' power requirements to obtain a total power requirement for the vehicle.

3.2 Constraints

By the year 2005 NASA experts believe to have a lunar base established which will use regenerative fuel cells and photovoltaics to serve as the primary power source for the base. This system can provide a continuous supply of hydrogen and oxygen for the Lunar ARTS.

3.3 Power Calculations

3.3.1 Locomotion Calculations

3.3.1.1 Description

Before proceeding to the following section, the reader should understand the following terms:

1) Experimentation is used in the text as a theoretical process to be done in the future. The design of the LARTS wheel and reproduction of the lunar soil characteristics cannot be executed at this time.

2) Substitution of an inflatable tire for the LARTS wheel means that certain known empirical equations from earlier works for an inflatable tire are substituted for equations not yet derived for the LARTS wheel (This occurs in the rolling resistance subsection Equation 2. All equations are clearly referenced). This by no means implies that an inflatable tire is proposed, considered, and/or will replace the LARTS wheel. However, if by some means in the near future, the LARTS wheel material characteristics and overall design can closely resemble a pressurized rubber tire, then the results of this section can be utilized efficiently.

3) Finally, the term, tire, is used to reference the inflatable tire. The term, wheel, is used to reference the LARTS wheel.

Locomotion energy of each of the three Lunar ARTS carts is calculated to find the needed energy and power for a 75 km (47 mi), 8 hr (continuously moving) Lunar ARTS excursion. (although no motors are mounted on the third cart, an individual energy analysis is calculated as if there were. This energy compared to the pulling energy of the third cart is in error of less than 2 %)

3.3.1.2 Additional Constraints

Because no direct equations are given for the type of wheel design incorporated on the Lunar ARTS, substitution must be implemented. For the locomotion requirements, an inflatable tire is substituted for the LARTS wheel assuming certain characteristics such as wheel stiffness and flexibility comparable to the LARTS design. Experiments must be made on the wheel to yield the following parameters: (1) wheel ground contact length, (2) wheel ground contact width (constant of .75 m), (3) wheel deflection stiffness, and (4) coefficient of rolling resistance [2] . The substitution yields slightly higher values than other Lunar rover vehicle testing, (i.e., Apollo Lunar Rover). Therefore, this substitution provides a reasonable factor of safety in its results. However, exact figures and factors of safety will only be revealed through experiment.

3.3.1.3 *Lunar Surface*

The LARTS travels over different angles of terrain, each angle corresponding to a percentage of the total terrain traversed. As shown in Table 3.1

The five soil conditions are characterized by the following parameters:

k_ϕ (friction modulus of deformation) $\frac{N}{m^{n+2}}$

n (exponent of sinkage)

k_c (cohesive modulus of deformation) $\frac{N}{m^{n+1}}$

C (soil cohesion) $\frac{N}{m^2}$

K (slip coefficient) m

ϕ (angle of friction) rad

3.3.1.4 *Wheels*

Assuming a uniform loading on each cart, each 2.3m (7.5 ft) diameter wheel will sustain a nominal load in lunar weight: 1) Cart 1, Men, Tools, Navigation and Computers; 596.82 N (134.18 lb), 2)Cart 2, Power Systems; 771.16 N (173.37 lb), and 3)Cart 3, Payload Carrier; 764.62 N (171.90 lb). Referring to the Locomotion Energy Calculations Program (appendix B.1), the nominal weight on each wheel (because of the symmetric loading, both wheels will endure the same loading for each cart) is calculated for each angle. The average ground pressure under each wheel is calculated from the ground contact length and ground contact width of each wheel. Because of the unusual design of the Lunar ARTS wheel, the contact ground length and width are constants to be derived experimentally. Hypothetical ground contact length and width are 1.0 m (39.37 in) and 0.75 m (29.53 in) respectively for good traction on the most slippery soil type at a 30-degree angle. The final result for the locomotion energy is made on these estimates and the wheel should conform to them, as feasibility requires). Wheel sinkage for the required angle and soil type is calculated, and would usually contribute to a corrected ground pressure under each wheel. However, because an empirical equation must be made to substantiate corrected pressure and because sinkage is on the scale of millimeters, the original pressure calculated becomes a close estimate of the true pressure (the error in corrected pressure is less than one per cent). The sinkage does however contribute to bulldozing and compaction resistances discussed later.

3.3.1.5 *Resistances*

Resistances are calculated for each wheel from the above parameters.

The rolling resistance is:

$$Rr = fi + Wni \tag{1}$$

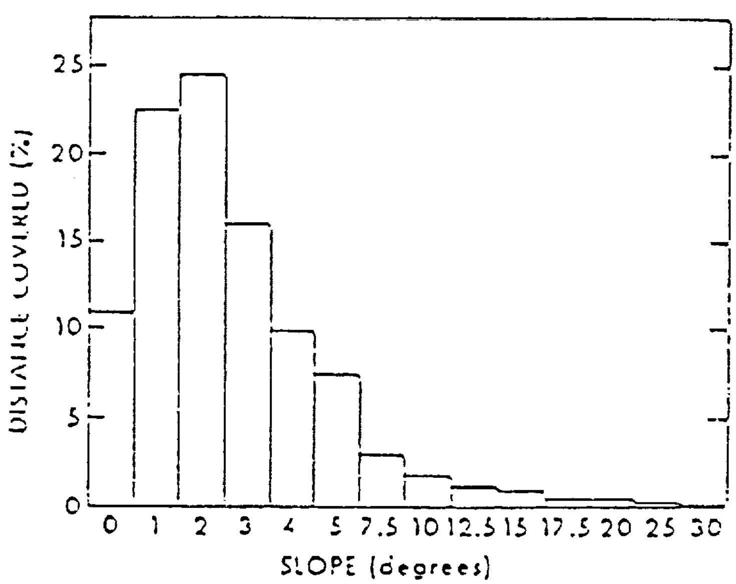
where Rr is the rolling resistance in N, fi is the coefficient of rolling resistance, and Wni is the nominal weight on each wheel for the given cart [2].

Because of the unusual design of the LARTS wheels, fi can only be found experimentally. Therefore, substitution of an inflatable tire given the same contact length and width chosen above with the same diameter is utilized. The result is a close but higher approximation to the rolling resistance to the Apollo LRV wire mesh tire. Assumably, an inflatable tire substitution would give a worse case scenario for rolling resistance. The wheel's rolling resistance, ground contact length, and ground contact width must be chosen experimentally. However, experimentation is impossible here because no facilities exist to reproduce the soil characteristics and the full scale wheel. Thus, until such experiments are done, substitution is an effective mean. For a flexible inflatable tire on a hard surface:

$$Rr = 5.1 + \frac{5.5 + 18W}{p} + \frac{8.5 + 6W(\frac{L}{100})^2}{p} \tag{2}$$

Table 3.1. Lunar surface characteristics obtained through Apollo mission experiments. Note that most of the traveling is up a two degree slope over a loose dust surface. This surface makes up 84 per cent of the Lunar ARTS' trip. (Courtesy NASA and F. Pavlics on Locomotion Energy)

SOLID ANGLE (Degrees)	PERCENT OF TOTAL DISTANCE TRAVELED	SOIL PARAMETERS $k_c = 0$, $C = 0$, $\phi = 32^{\circ}$
0	11.0	$k_\phi = .5$
1	22.5	$n = .5$
2	24.5	
3	16.0	Loose dust
4	10.0	
5	7.5	$k_\phi = 1.0$
7.5	3.0	$n = .75$
10	1.8	$k_\phi = 3.0$
12.5	1.2	$n = 1.0$
15	1.0	
17.5	.5	Loose sand
20	.5	
25	.3	$k_\phi = 6.0$, $n = 1.25$ Hard sand
30	.2	Hard surface



where W is the tonnage of the *vehicle* in lunar lbf divided by 2000 earth lbf, p is the pressure inside the tire in earth $\frac{kg}{cm^3}$, and L is the length of the trip in km [3] . Note that this inconsistency of units is due to the inconsistent dimensions that the factors in equation 2 must possess.

By experimenting with different pressure ratings to a desired contact length and width, the coefficient of rolling resistance is chosen and Rr is calculated from the program. A comparison for rolling resistances of the three carts to different assimilated pressures is given in Table 3.2 . Remember though, if the contact length is changed then logically the pressure must change. Therefore, for Equation (2) and from Table 3.2, fi must change to the desired pressure for that change in contact length. Figure 3.1 and Figure 3.2 , respectively, represent the rolling resistance vs the wheel load 25 psi on all three carts, and final power outputs for the entire LARTS for the aforementioned parameters compared to the tire pressure input.

Bulldozing resistance is calculated for each tire:

$$Rb = 0.5\gamma(Bi)za^2\tan^2(0.7854 + 0.5\phi) + 2C(Bi)za\tan(0.7854 + 0.5\phi) \tag{3}$$

where Rb is bulldozing resistance in N, za is wheel sinkage in m, Bi is the ground contact width, γ is soil density in $\frac{N}{m^3}$, C is soil cohesion in $\frac{N}{m^3}$, and ϕ is average soil angle of friction in radians [4] . These values are as follows:

$\gamma = 13571.681\ \frac{N}{m^3}$ [5]
$\phi = 0.6458$ radians[6]
$C = 0.0\ \frac{N}{m^3}$ [2]
$Bi = 0.75$ m

and za is analytically calculated by the Locomotion Energy Program.

Compaction Resistance for each wheel is calculated as follows:

$$Rc = Bi(\frac{kc}{Bi} + k_\phi)\frac{(za^{n+1})}{n+1} \tag{4}$$

Refer to Table 3.1for parameter values [2].

Grade Resistance for the total vehicle is given by:

$$Rg = Wni(WT)\sin\theta \tag{5}$$

where WT is the number of wheels on each vehicle [2].

The total vehicle steady-state motion resistance in Newtons is:

$$Rt = RrT + RbT + RcT + Rg \tag{6}$$

where RrT, RbT, and RcT are the rolling, bulldozing, and compaction resistances multiplied by WT [2]. The total vehicle steady-state motion resistance vs. wheel load for each cart on each soil type and corresponding slopes (refer Table 3.1) is given in Figure 3.3 .

3.3.1.6 Slippage

Knowing the steady-state motion resistance (thrust), the slip was interpolated. A wheel slip to thrust curve was not found for the LARTS, and therefore, an upper and lower limit of the slip was applied. For a thousand cases of slip, the slip (a percentage value) was inputted into the following equation:

$$H = (C(Ai) + Wni\tan\phi)(1 - \frac{K}{sli}e^{\frac{-sli}{K}}) \tag{7}$$

Table 3.2. Rolling resistance coefficients at varying pressure for the LARTS.

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#	PSI	CART I	CART II	CART III
1	1	0.61	0.48	0.48
2	2.5	0.25	0.20	0.20
3	5	0.13	0.10	0.10
4	10	0.073	0.058	0.058
5	15	0.053	0.042	0.042
6	20	0.044	0.034	0.035
7	25	0.038	0.030	0.030
8	30	0.034	0.026	0.027
9	35	0.031	0.024	0.024
10	40	0.029	0.023	0.023
11	45	0.027	0.021	0.021
12	50	0.026	0.020	0.020

POWER (kW)

	PSI	CART I	CART II	CART III	LRV
1	1	3.88	4.03	4.03	11.94
2	2.5	1.77	1.90	1.89	5.56
3	5	1.08	1.19	1.19	3.46
4	10	0.73	0.84	0.83	2.40
5	15	0.62	0.72	0.72	2.06
6	20	0.56	0.66	0.66	1.88
7	25	0.53	0.63	0.62	1.78
8	30	0.50	0.60	0.60	1.70
9	35	0.49	0.59	0.58	1.66
10	40	0.48	0.57	0.57	1.62
11	45	0.47	0.56	0.56	1.59
12	50	0.46	0.56	0.55	1.57

Figure 3.1. Wheel load versus rolling resistance.

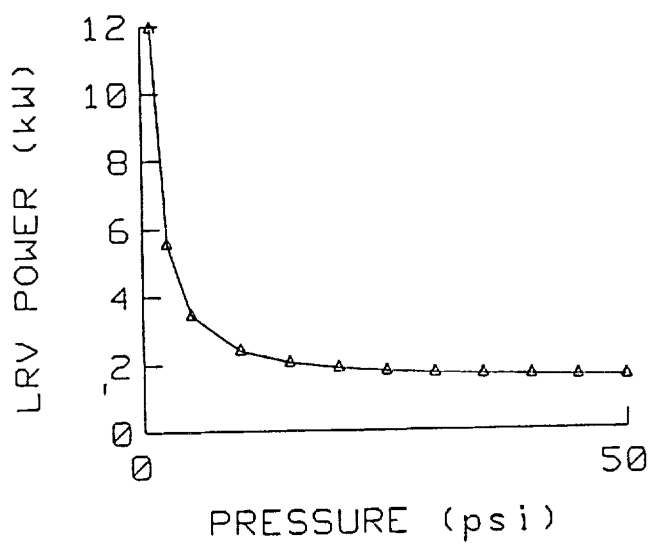

Figure 3.2. Lunar ARTS power versus substituted pressure.

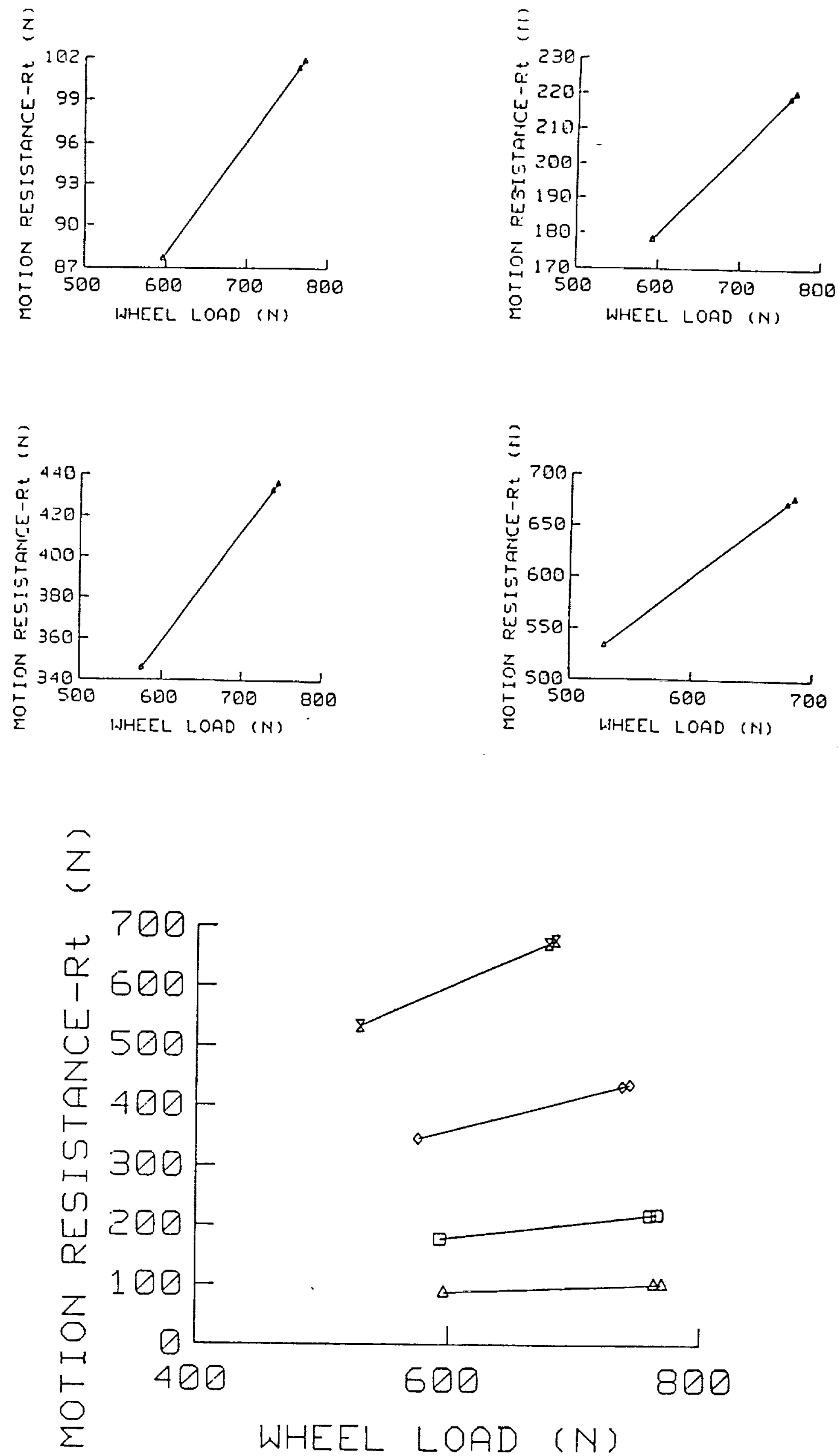

Figure 3.3. Wheel load versus steady state motion resistance for the Lunar ARTS.

where s is the slip in decimal notation, H is the thrust in N, and l_i the wheel ground contact length in m [2]. Knowing H, an upper and lower bound was found above and below the known H, and s was interpolated to correspond to the known H. This thrust is to equal the total vehicle steady-state motion resistance, Rt above. Refer to the Locomotion Energy Program for further explanation. Figure 3.4 provides a slip vs. thrust curve for each of the three carts to run up a certain slope corresponding to a fraction of the total distance the LARTS travels (refer Table 3.1) on different soil types. Slippage (s) figures directly into the energy equation, Equation (8).

3.3.1.7 Energy

The energy equation is calculated for each slope, θ, and its corresponding length of travel and soil type as follows:

$$E = \frac{T(0.00123Rt)}{dte(1-s)} \tag{8}$$

where E is the energy to go up each slope (where each slope contains a fraction of the total distance the Lunar ARTS travels) in $\frac{kw-hr}{km}$, T is the corresponding length of travel up the slope (refer Table 3.1), dte is the drive train efficiency which is estimated at 0.95 since the motors are so close to the wheels, and s is the slippage [2]. Note that Rt must be converted to lbf in order to use Equation (8).

3.3.1.8 Static and Dynamic Energy

The total steady-state (static) locomotion energy is the sum of all energies making 100 per cent of the total distance traversed.

From two-dimensional dynamic analysis run for the Apollo lunar rover (such a dynamic analysis is not readily available at the moment), the dynamic or damping locomotion energy came to be approximately 25 per cent of the static case [7] .

3.3.1.9 Cart and Gross Energy

Thus, from totaling the static and dynamic energies which is equivalent to approximately 1.25 times the static energy, the cart locomotion energy is calculated.

By factoring in the drive system efficiency (dse), which in this case is estimated at 0.95 because of the drive motors so close to the wheels and a separate motor for steering, the gross locomotion energy is derived by:

$$GE = \frac{LET}{dse} \tag{9}$$

where GE is the gross locomotion energy in $\frac{kw-hr}{km}$ and LET is the cart locomotion energy in $\frac{kw-hr}{km}$ [2].

3.3.1.10 Total Locomotion Energy

In addition to the factors thus far discussed, "energy is also required to accelerate, brake, and steer the vehicle, and to overcome losses due to surface roughness. Since no simple methods are presently available to treat these factors in a rational manner, it is necessary to provide an energy reserve. At the present time, GM DRL is using a reserve of 35 per cent of the gross energy" GE [2]. Therefore, the total locomotion energy for a cart is given by:

$$GET = 1.35GE \tag{10}$$

This series of calculations (equations 1-10) are repeated for each of the three carts. The sum of the total locomotion energies for each cart makes up the total locomotion energy of the LARTS.

CART I (268 lb)

#	SLOPE(°)	SLIP%	THRUST(lb)	SOIL TYPE
1	0	0.60	10.36	Loose Dust
2	1	0.61	15.04	
3	2	0.62	19.72	
4	3	0.63	24.39	
5	4	0.64	29.03	
6	5	0.65	34.35	
7	7.5	0.68	45.77	
8	10	0.71	57.12	Loose Sand
9	12.5	0.75	67.91	
10	15	0.79	78.26	
11	17.5	0.83	88.1	
12	20	0.88	97.35	
13	25	0.88	113.25	Hard Sand
14	30	1.02	126.61	Hard Surface

CART II (347 lb)

#	SLOPE(°)	SLIP%	THRUST(lb)	SOIL TYPE
15	0	0.59	10.82	Loose Dust
16	1	0.60	16.87	
17	2	0.61	22.91	
18	3	0.62	28.94	
19	4	0.63	34.94	
20	5	0.65	42.12	
21	7.5	0.68	56.86	
22	10	0.70	71.43	Loose Sand
23	12.5	0.74	85.37	
24	15	0.78	98.74	
25	17.5	0.82	111.44	
26	20	0.87	123.38	
27	25	0.86	143.68	Hard Sand
28	30	1.00	160.93	Hard Surface

CART III (343 lb)

#	SLOPE(°)	SLIP%	THRUST(lb)	SOIL TYPE
29	0	0.59	10.80	Loose Dust
30	1	0.60	16.80	
31	2	0.61	22.79	
32	3	0.62	28.77	
33	4	0.63	34.72	
34	5	0.65	41.82	
35	7.5	0.68	56.44	
36	10	0.70	70.89	Loose Sand
37	12.5	0.74	84.71	
38	15	0.78	97.96	
39	17.5	0.82	110.56	
40	20	0.87	122.40	
41	25	0.86	142.54	Hard Sand
42	30	1.00	159.64	Hard Surface

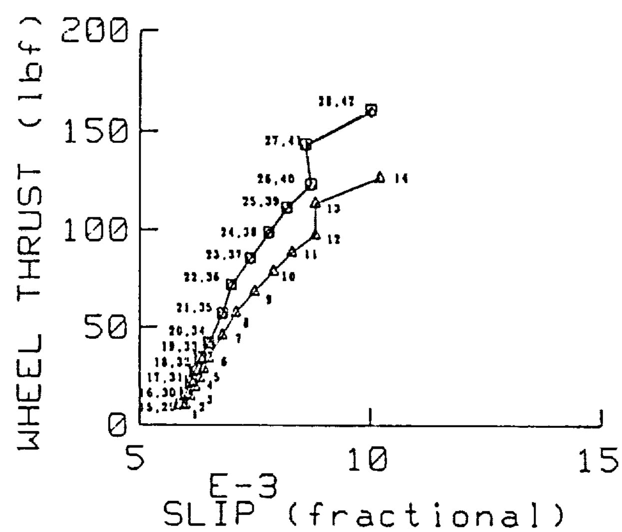

Figure 3.4. Slip vs wheel thrust on 14 different surface angles and 5 different soil types.

3.3.1.11 Power

The total power for the LARTS is then given by:

$$P = ETOTALx\frac{8}{75} \tag{11}$$

where P is the total power of the LARTS in kw,and $ETOTAL$ is the total locomotion energy of the Lunar ARTS for an eight hour running trip 75 km out [2].

Since a tire's maximum pressure (on a large tractor) is 35 psi (241 kPa), estimated pressure for a 1.0 m (3.3 ft) contact length, 0.75 m (2.5 ft) contact width and 2.3 m (7.5 ft) diameter tire, should be in the range of 15-35 psi (average 25 psi or 172 kPa) or between 2.06 and 1.66 kw power, respectively (refer Table 3.2). On average, 25 psi was taken at 1.78 kw with a factor of safety of 1.3. From 2.3 kw (1.78 x 1.3) for 25 psi tires, each motor would supply a required 0.58 kw (0.78 hp). The program in appendix B.1 gives a locomotion power requirement of 2.0 KW for the Lunar ARTS (for a 10 hr mission).

3.3.2 Vehicle Component Calculation and Power Program

In determining the power needed to be supplied by the vehicle, the components which need power to operate were determined. The power needed for each component was either determined by previous Lunar ARTSs or previous experience with the components. These components were placed in a program and were split up by the cart in which it would be placed. An extra 10% was added for each cart for the amount of power lost to heat. The total number for all of the components was added to the locomotion energy to determine the total power requirement. The locomotion energy calculations included a 10a total power determined, the amount of power needed to account for the 70% efficient fuel cells was added to this total as well as an error of 5%. This error was added so that if slight changes occur later in the project, a new fuel cell system would not have to be specified. The program and its output can be found in appendix B.1. The total power necessary is 4.0 kilowatt (kW) and the energy needed is 60.00 kilowatt-hour (kWhr) for a 10 hour mission with a 50

3.4 Fuel Cells

3.4.1 Description

When a total power requirement was obtained it was necessary to decide on what power system to use. Batteries were ruled out as a power system. Calculations in appendix B.2 showed that batteries could not be used because of the large weight requirement. Fuel cells were chosen as the means for propulsion for the Lunar ARTS vehicle. Fuel cells are a technology that has already been proven successful in many space applications.

Fuel cells are classified according to: type of electrolyte, type of electrode, type of fuel, temperature, and type of catalyst [8]. Section 3.4.3 will cover the type of fuel, the storage system and the tank design. Section 3.4.4 will cover the type of electrodes, the type of electrolyte, type of catalyst, and the temperature at which the fuel cell operates.

3.4.2 Additional Constraints

Currently fuel cells are 60% efficient with a projected efficiency of 70% by the year 2005. With an increasing demand for fuel cells, it will be possible to order and fabricate a set of fuel cell tanks to a desired specification within a year's time. The Lunar ARTS vehicle will contain the storage and reactant tanks and the fuel cell stacks onboard the vehicle, but the fuel cells will not be regenerative. The by-product of water from the fuel cells will be used in the heat rejection system and will be stored in a separate tank on the vehicle. This will be brought back to the base to be electrolyzed by photovoltaics. A back-up system will be used to ensure that the astronauts can safely be returned to the base if the original system fails. The back-up system will be explained in Section 3.4.3.

3.4.3 *Storage System and Tank Design*

The reactants which are used in the fuel cell stacks are hydrogen and oxygen with the by-product being heat and water. The reactants can be stored either as pressurized gases or as cryogenic liquids [9]. Storing the reactants as cryogenic liquids reduces the size, weight, and meteoroid vulnerability of the storage tanks. Reactants will be stored as cryogenic liquids and will be heated upon leaving their storage tanks to be vaporized prior to entering the fuel cell stacks (the hydrogen and oxygen must enter the stacks as a gas for operation of the vehicle). After being cooled the water is stored as a liquid.

The liquid hydrogen and liquid oxygen will be stored as cryogenic liquids in tanks that consist of a spherical aluminum 2219 - T6 inner pressure vessel and a concentric aluminum 6061 - T6 outer shell. There are 90 layers of insulation between the inner and outer sphere. The multi-layer insulation is 90 layers of double aluminized mylar ($\epsilon = .035$) with silk netting between each layer. There are also two vapor-cooled shields between the inner and outer vessels. The vapor-cooled shields together with the Joule Thomson valve and pressure vessel wall heat exchanger make up the thermodynamic vent system which provides thermal protection from radiant heat flux and maintains pressure in the tanks. The mass of the thermodynamic vent system will be included in the plumbing. The exit pressure will be controlled by a pressure regulator. This thermodynamic vent system allows the hydrogen and oxygen to leave the tanks as a vaporized gas. The soft outer shell tank and the multi-layer insulation is sufficient in providing micrometeoroid impact protection. This design is based on a Beechcraft design and is shown in Figure 3.5 [10]. The liquid hydrogen and liquid oxygen will be stored at 20.7 MPa (3000 psi). The water will be stored in tanks made of a filament wound Kevlar 49/epoxy matrix. In determining the mass and volume of reactants, the necessary amount was increased by 5% in order to account for reactant residual. In sizing the tanks, the volume needed was increased by 10% to accommodate maximum filling[9]. The tank sizing program and output are located in appendix B.3.

The hydrogen tanks will have an inner pressure vessel diameter of .1071 m (4.217 in) with a thickness of .0095 m (.374 in). The insulation and vapor cooled shields will have a thickness of .0230 m (.906 in). The outer pressure vessel will have a diameter of .1606 m (6.323 in) and a thickness of .0037 m (.1471 in). This will give a storage volume of .0375 m^3 (1.325 ft^3) and a storage capacity of 2.520 kg (5.56 lb). The tank's mass is 8.227 kg (18.14 lbf) empty. The consumption rate of hydrogen is .04 kg/kWhr. The reactants will be stored at -251 °C (-420 °F).

The oxygen tanks will have an inner pressure vessel diameter of .0836 m (3.301 in) with a thickness of .0074 m (.293 in). The insulation and vapor cooled shields will have a thickness of .0230 m (.906 in). The outer pressure vessels will have a diameter of .1362 m (5.361 in) with a thickness of .0032 m (.125 in). This will give a storage capacity of .0180 m^3 (.635 ft^3) and a storage capacity of 20.16 kg (44.45 lb). The tank's mass is 5.042 kg (11.12 lb) empty. The consumption rate of oxygen is .32 kg/kWhr. The oxygen will be stored at -181 °C (-294 °F).

Water is a by-product of the fuel cell system, will be stored in tanks and will be converted back into hydrogen and oxygen at the lunar base. The water is stored at a pressure of 2.2 MPa (319 psia). The water tank will be a spherical tank with a inner diameter of .0920 m (3.623 in) and a thickness of .0003 m (.012 in). This tank will give a storage capacity of .0238 m^3 (.840 ft^3) and a storage capacity of 23.76 kg (44.45 lb). The tank's mass is .01 kg (.022 lb) empty. The production rate of water is .36 kg/kWhr.

The tanks were designed using the yield stress of the aluminum. The proof factor (factor of safety) used was 1.3 and the proof pressure was equal to 4500 psi (the product of the proof factor and the operating pressure). The tanks have to be stored properly in order to provide prevention of mechanical damage, prevention against exposure to advance environment which could cause corrosion and stress, and prevention of induced stresses due to storage fixture constraints. The vessels have to be experimentally tested before being placed on the moon[11].

The storage and reactant tanks will be held in place using the same design as stated in section 1.1.6 in the Beechcraft report [10]. The material used will be aluminum 2029-T6 to ensure compatibility with the storage tanks and use of light mass materials.

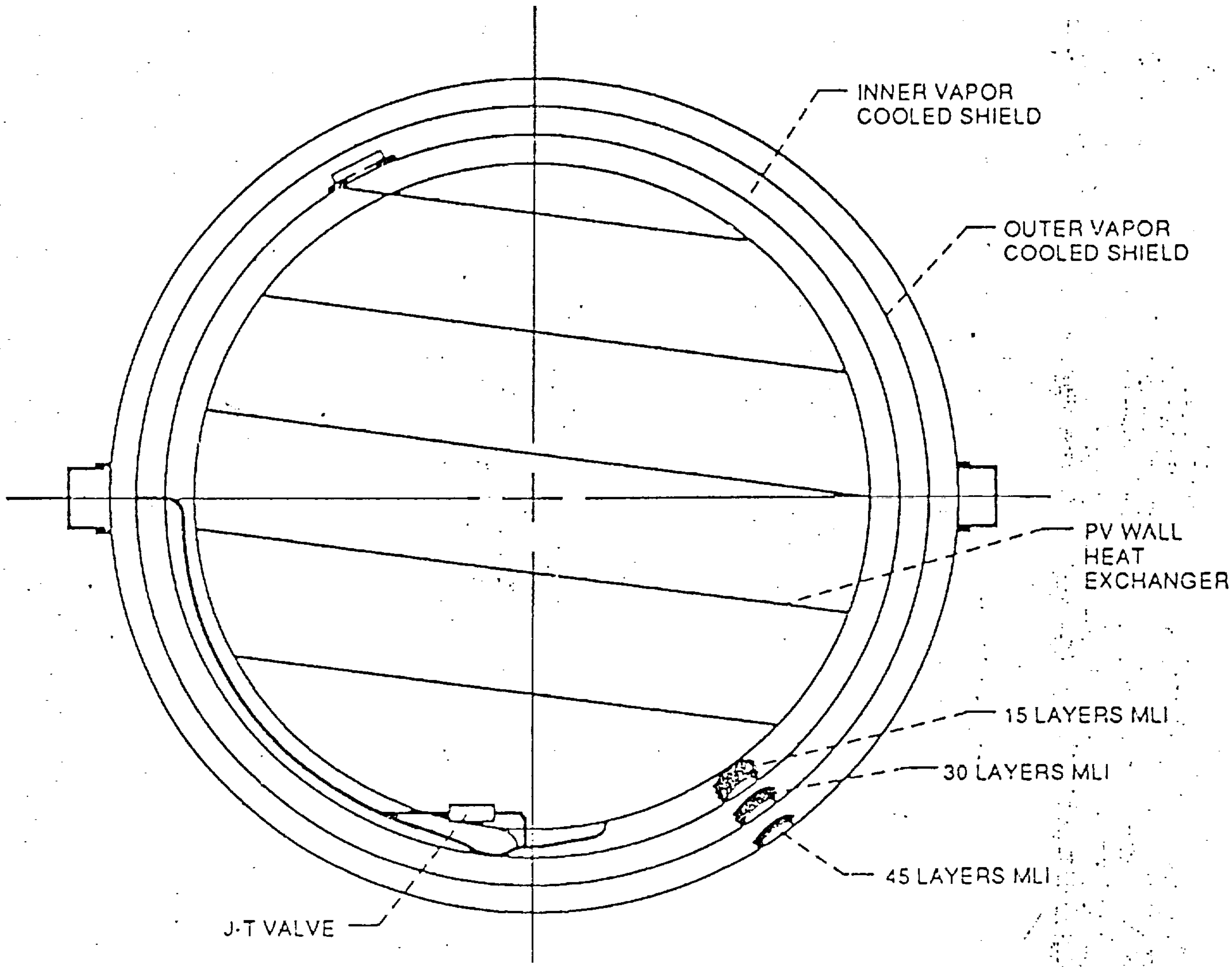

Figure 3.5. Schematic of fuel cell storage tanks.

The two options that could be used as a back-up system for power were to duplicate the plumbing from the tanks to the fuel cells or to use two sets of tanks. Since failure of the fuel cell system usually occurs in the plumbing, it was decided to use an additional hydrogen, oxygen, and water storage tank of the same dimensions as the original tanks which will be placed on the same cart as the primary power system. The two sets of tanks and plumbing will be used alternately so that one set will not be clogged or contaminated from prolonged nonuse of the system.

3.4.4 *Stacks*

After the hydrogen and oxygen gas leave the storage tanks as vaporized gas, they are fed into the stack. The stack is made of many small individual cells each containing an anode, a cathode, and an electrolyte. In the hydrogen-oxygen fuel cell, hydrogen gas is fed into the anode and then consumed by the electrochemical reaction which separates into hydrogen ions and electrons. The ions and electrons are then released out to the external circuit for driving an electrical load (supplying power). The cathode (oxygen electrode) reacts with hydrogen ions and the electrons electrochemically to form water and heat. The electrolyte is located between the two electrodes and serves as a transporter for the ions and electrons in the electrochemical reaction [12]. Figure 3.6 shows the electrochemical process of a single cell. The heat from the cell must be rejected and the water must be removed from the fuel cell during operation.

The electrolyte in the stacks determines the type of fuel cell. In the past, the most efficient type of cell was an alkaline fuel cell (used on the space shuttle today [13]). This type of cell uses a liquid hydroxide as the electrolyte between the electrodes. This type of fuel cell proved to be successful on many Apollo missions [14]. Heat and water removal in the cell were done by a hydrogen coolant loop. A glycol-water secondary coolant loop was also employed. The operating pressure of the system and the relative pressure differentials, however, affected the fuel cell performance.

An alternative to the alkaline fuel cell is the PEM (Polymer exchange membrane). This type of cell uses hydrogen and oxygen at the electrodes, but uses a solid polymer between the electrodes. In the past this type of cell was not as efficient as the alkaline, but offered many advantages over the alkaline fuel cell if a more efficient membrane could be devised [14]. Just recently, Dupont created a new type of membrane material that could be used in the fuel cell. With additional processing carried out by General Electric, a new type of solid electrolyte was produced with negligible difference in efficiency between the alkaline fuel cell and the PEM. [12] When saturated this membrane serves as an excellent ionic conductor and serves as the only electrolyte required in the system. Other SPE advantages are: long stable life (up to 20000 hours), no electrolyte blow-through (5000 psi differential pressure with proper membrane support), and a simple start/stop without inerting (after initial start up which takes approximately 10 seconds)[15]. Finally, the SPE fuel cell can have a stable instantaneous full load applied without any difficulty since the reactants are demand fed.

The Lunar ARTS will use PEM fuel cells as the choice for power production. This will have a smaller mass than an alkaline fuel cell system. Water removal from the cells can be done by using the same loop for both water removal and cooling chamber [15]. Figure 3.7 shows a cut-away view of this concept for a single cell. This can be accomplished by using a porous separator (titanium membrane) between the cooling loop and the oxygen loop of the cell. The porous titanium plate (when wetted with water) allows water to pass, but blocks oxygen flow when the oxygen pressure exceeds the water chamber pressure up to a bubble pressure point (The bubble pressure point is sufficiently above the operating differential pressure to assure that gaseous oxygen does not pass into the water chamber) [15] . The solid polymer electrolyte used will be Nafion. Since the electrolyte is solid, the electrodes (or catalyst structure) will be a thin film, pressed on each side of the electrolyte (the electrodes will not have to serve any structural purposes as their only purpose is to provide sufficient catalytic activity to achieve desired performance levels [15]). The oxygen electrode material will be teflon bonded platinum while the hydrogen electrode material will be platinum catalyst blend.

The lunar ARTS will require one stack for a storage capability of 59.55 kWhr. In order to prevent liquid water from filming on the oxygen electrode (and thus decreasing the performance of the fuel cell), a hydrophobic film will be incorporated on the electrode. For a life of 20000 hours, the cells should operate at a temperature

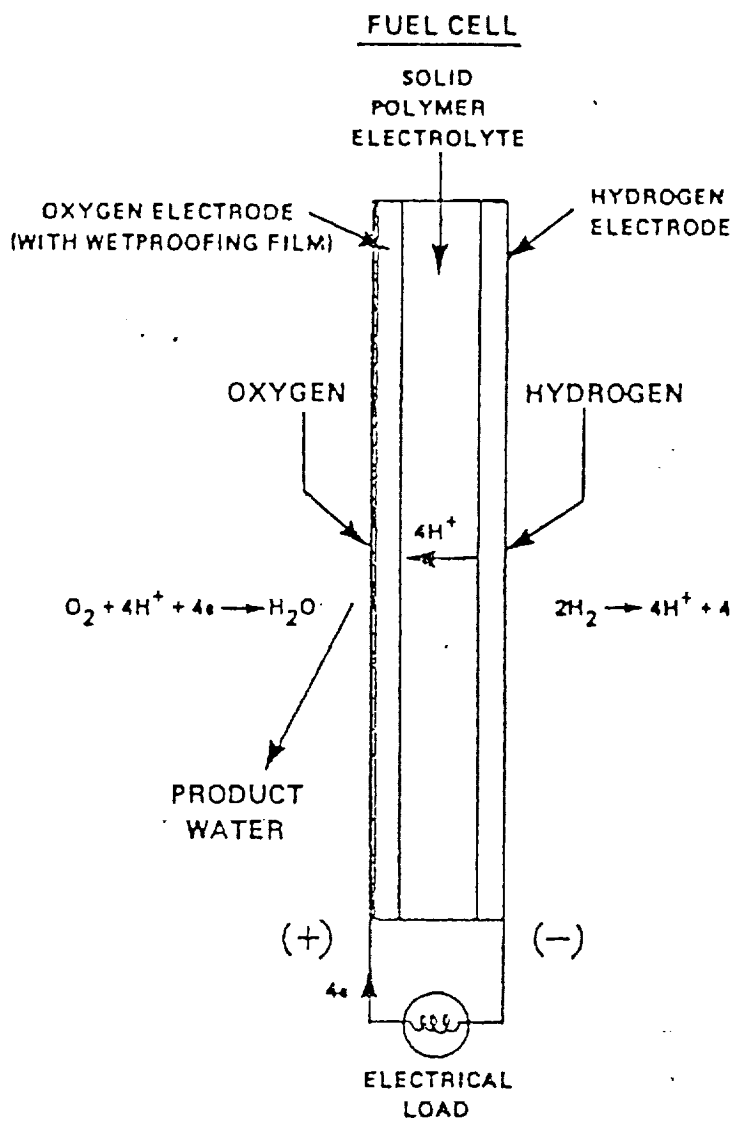

Figure 3.6. Electrochemical process of a single cell.

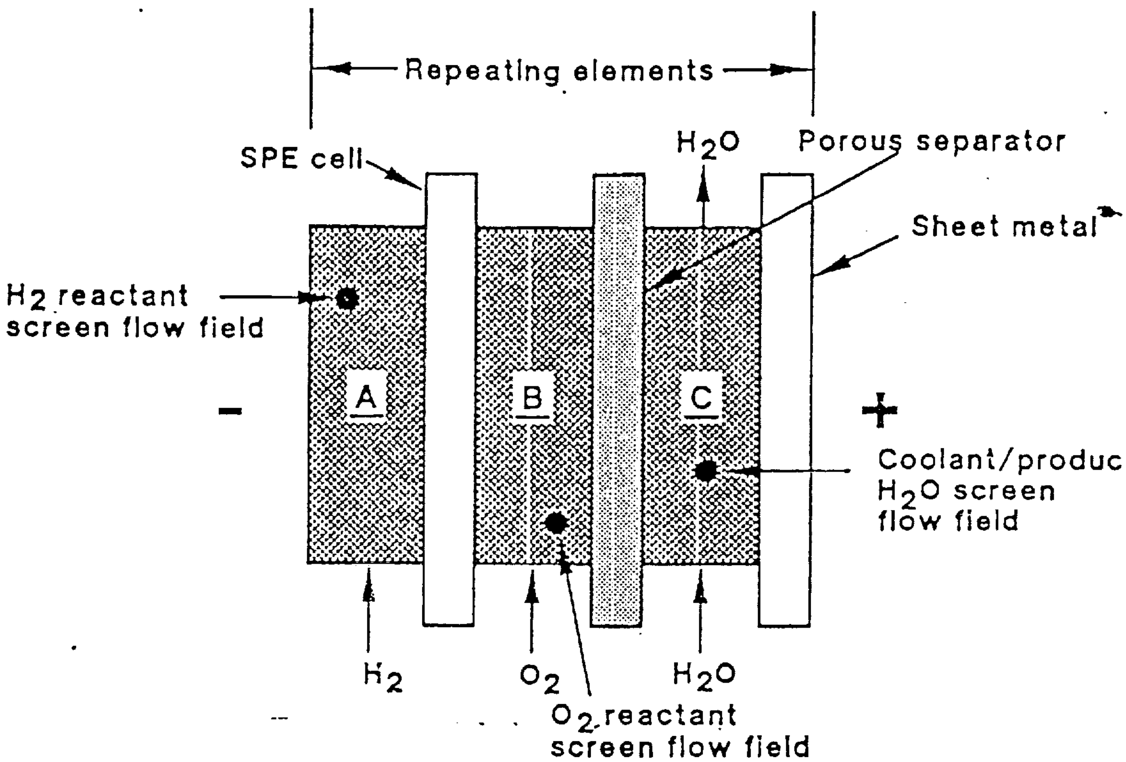

Figure 3.7. Cut away view of a single cell cooling process.

of 96 °C (already currently proved today)[16]. Cell temperature is controlled by a temperature regulating valve. The temperature should not rise more than 6 °C (10 °F) from its original operating temperature when at maximum load. In order for the fuel cells to output 5.955 kW of power the voltage will be .9 volts/cell and 200 amps/ft^2. Operating with at these parameters and at a pressure of 60 psia (.4 MPa) and temperature of 180 °F (82.2 °C) the specific mass is 40.0 N/kW and a specific volume of .0042 m^3/kW (by General Electric) [12]. The stacks will have a mass of 24.302 kg and a volume of .8933 ft^3. The plumbing will have a mass of 13.505 kg. Each cell is 1 ft^2. The stack is .564 ft (.172 m) in diameter with a height of .893 ft (.272 m) (see appendix B.3). Total mass for the tanks, fuel, stacks and plumbing will be 153.01 kg (337.53 lbf). The backup system which includes the tanks, reactants and plumbing will add an additional 71.099 kg (156.3 lbf) making the total mass of the power system to be 224.1 kg (494.25 lbf).

3.5 Summary

In order to determine a power requirement for the Lunar ARTS, initial calculations for the locomotion in conjunction with other components' power requirements had to be obtained to get an overall power requirement for the vehicle. Once the power requirement was determined, fuel cells were the power system of choice. The power system used on the Lunar ARTS vehicle to produce 5.955 kW of power is a Polymer Exchange Membrane (PEM) fuel cell system. This system uses hydrogen and oxygen as reactants which are stored as cryogenic liquids. The cell generates electrons (which generate the power to operate the Lunar ARTS),heat (which is to be rejected by a coolant loop), and water. This system has a duplicate set of hydrogen and oxygen tanks which are used as a back-up if the system fails. The system has an expected life of 20000 hours and is dependant upon a regenerative fuel cell system at the lunar base. Figure 3.8 shows the PEM fuel cell system as it would be placed on the cart.

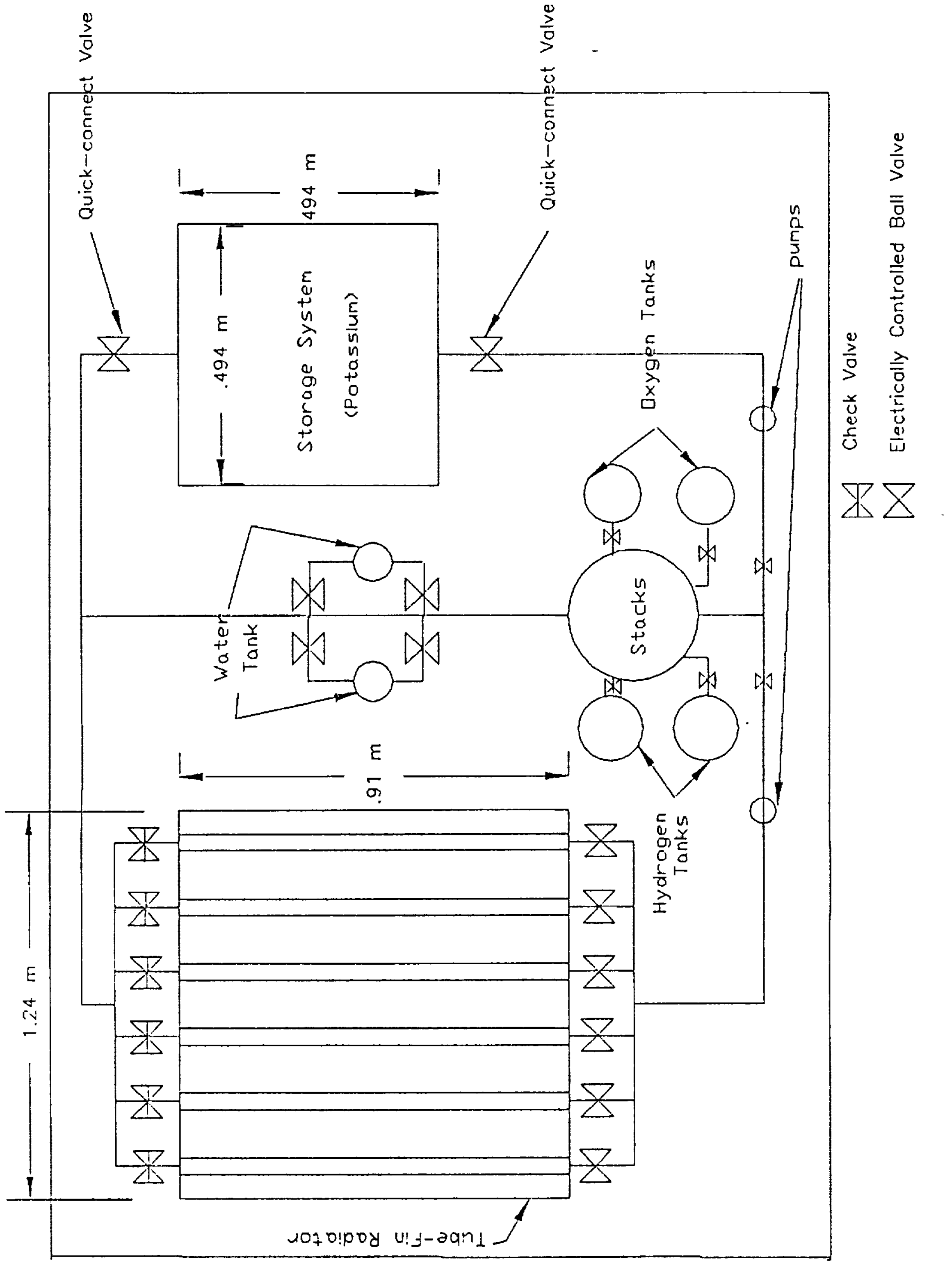

Figure 3.8. Fuel cell system on second cart.

4. Mobility

4.1 Introduction

Mobility of the LARTS incorporates five sections: suspension system, wheel design, hitch design, chassis design and modeling, and center of mass. The design and analysis of each was preformed by independent groups, with system integration incorporated throughout the design process. This was accomplished by having all design personnel working on the mobility section meet weekly to discuss integration issues of the mobility components.

4.1.1 Suspension System

The suspension system is composed of three major components: flexible hemispherical wheels, a four-bar double wishbone linkage, and a compound spring shock absorber. The double wishbone linkage limits the spindle assembly to vertical motion, thus, keeping the tracking of the wheels in contact with the lunar surface. The compound spring in the shock absorber is coupled with flexible hemispherical wheels, and the system was modeled in a DADS to determine the damping constant.

The spindle assembly at the end of the control arms holds the driving and steering motors as well as the gearing and linkages used to transmit the power effectively. The primary steering is accomplished by electronic servo-motors that rotate a spindle plate. The secondary, or backup, steering is an open loop on/off switch control operated from a power bus by means of a control stick or joystick.

4.1.2 Wheels

The wheels of the LARTS are a hemispherical Kevlar polymer composite shell supported on the inside by a polar array of geometrically curved ribs and protected on the outside by a Mylar cover. Of utmost importance to the wheels is their dynamic flexibility, during day and night operation. The deformation of the shell as it rolls will be supported by the rib array and protection against lunar dust build up will come from the mylar cover. This design offers a large ground contact area to provide adequate traction on the lunar surface while minimizing the problem of lunar dust.

4.1.3 Hitch

The three carts of the LARTS are permitted pitching, yawing and rolling motion relative to each other. The connection between each is accomplished by using ball and socket joints. Because the carts are two wheel vehicles, they are susceptible to pitching and to a lesser extent yawing. The hitch must limit this motion of the carts due to external forces, while remaining flexible. A polar array of springs mounted between the hitch and cart uses different spring constants to constrain the cart to the proper vertical and horizontal motion. The hitch connecting the second and third carts is an ordinary ball and socket hitch.

4.1.4 Chassis

Each of the three carts is a "shoebox " frame with wall supports and mounting beams for the suspension system. An open top was chosen instead of a closed truss design to allow an easier entry and/or loading of the mass around the center of the cart. This would reduce the task of balancing the center of mass from mission to mission. Lightweight material with radiation "shields " conducive to the needs of the heat rejection group will make up the walls of the carts.

The first cart is primarily for transportation of astronauts; navigation equipment, and computers are also kept in a rear storage compartment. This is permanently fixed to the second cart, which holds the power system. The third cart is for transporting hand tools, regolith accessories, and soil samples. Because the first cart is designed to carry the astronauts, its design will vary slightly from the basic design of the second and third carts.

4.1.5 *Center of Mass*

Using a local reference frame defined on each carts, the center of mass for each maybe readily determined. Because equipment is stored in various places that change from mission to mission, a balance system is used to position the center of mass over the wheel axis in the center of the cart. A balance is critical in a two wheel cart, because the any variation of the center of gravity from the center of geometry will result in uneven loading of the shocks from rolling moments, and/or preloading the hitch springs due to pitching moments.

4.1.6 *Seats*

The seats of the LARTS will be bench style. This enables easy entry and exit of the vehicle. The bench type seat is chosen to accommodate either one or two astronauts while keeping the center of mass in the center of the vehicle. If only one astronaut uses the rover he can position himself in the center of the bench and if two astronauts are riding in the cart, they can ride side by side to balance the cart. For easier entrance on the passenger cart, a step will swing into place offering support between the ground and cart.

4.2 Design Constraints

The mobility section embodies the dynamics and structures of the individual carts and well the LARTS as a whole. The LARTS must for day and night operation be able to withstand dynamic loading from normal operation (10 km/h), balance the center of mass for daily missions, and comfortably seat one or two astronauts for up to an eight hour journey.

4.3 Chassis

4.3.1 *Chassis Description*

In any space or flight design, the mass of the structure is of utmost concern. The design of the chassis for the lunar vehicle is based on this principle. An optimum design is one that supports all the specified loads with the necessary factor of safety (1.5) while using the minimum necessary materials. The basic design of each cart is a structural frame or chassis covered with radiation shielding paneling. The three carts of the LARTS are each slightly different in their load carrying functions, and therefore each design will have slight variations from the basic design.

4.3.2 *Additional Chassis Constraints*

The LARTS chassis must carry all axial loads, bending moments, and thermal stresses incurred during normal operations. In addition, the chassis must be well suited for attachment of the suspension system, radiation shielding panels, floor boards, and small mounting devices. The chassis of the LARTS must have a natural frequency that will not resonate under normal operation.

4.3.3 *Chassis Design*

An orthogonal three dimensional coordinate reference frame is set up on the LARTS with the following axes. The x-axis runs side to side along the "wheel axis, "the y-axis is in the vertical direction, and the z-axis traverses the length of the three carts.

The basic chassis is made of lightweight aluminum welded into a 4.5'x 6'x 9' "shoebox " frame. The frame has eight vertical supports, one at each of the four corners, and two additional supports along each side where the suspension system will be mounted. Additional inward triangular supports will be used for support against horizontal loads on the cart at each of the vertical supports.

The first cart, where the astronauts will ride, is an exception to the basic design. Because the wheels are so large, they do not permit side entrance to the vehicle. The front of the vehicle is thus transformed into a passageway for the astronauts. To support the walls on either side of the passageway, the front upper cross support is replaced by triangular support beams which mount to the floorboard. The upper structural members on the first cart is angled down 18.4° along the z-axis. This gives the front cart a slightly tapered shape, but does not change the overall structural design.

The third cart is designed to carry large samples of lunar regolith. It is essentially a bed made from sheets of a lightweight honey-comb sandwiched between thin aluminum sheet metal. These thin sheets are reinforced on the underside of the bed by planar triangular trusses parallel to the x-axis. These trusses distribute the regolith load evenly along the lower chassis structure.

4.3.3.1 Material Selection

The material specified for the chassis is Aluminum 2219 Titanium alloy with the following properties: $S_y = 51$ *ksi.*, $E = 10.6$ *Mpsi.*, $G = 3.9$ *Mpsi.*, $\alpha = 12.8x10^{-6}$ °*F*. This material was chosen because it has the high strength to weight ratio necessary for this type of design, and has been field tested and durable. By taking into consideration the surface finish, the shape factor, and the elevated temperatures, an endurance strength of 23.13 ksi was determined [17].

Temperature gradients that occur if the beams are partially exposed to sunlight will create negligible thermal stresses in the aluminum beams because of their high ductility. Temperature distributions were analyzed as a semiinfinite solid model and a lumped capacitance model both with equivalent coefficient of thermal radiation [18]. Lowered temperatures also did not have an adverse effect on the strength of the material. At a temperature of -220_oF the strength of aluminum increased significantly[19].

Ceramic materials have a lower range for the thermal coefficient of expansion than do the aluminum properties, but because there are still questions concerning the brittle nature in dynamic loading situations, this material was ruled out. By the year 2005, the use of a ceramic or composite material may be proven to better facilitate the chassis design.

4.3.3.2 Beam Geometry

The long beams that run along the edges of the chassis are subjected to tensile and compressive loads, bending moments, and thermal stresses. Design against axial loads due to simple tensile or compressive forces is based on a straight forward dependence on cross-sectional area of the beam. Bending moments are carried by choosing appropriate geometry and orientation of the beams such that high inertia properties resist these loads.

Because of the orthogonality of the chassis shape, side forces and bending moments will be parallel to the axes of the frame. L-beams oriented perpendicular to these side forces have the necessary inertia properties in the vertical and horizontal direction while minimizing the cross sectional area and weight. A small geometric program was written to calculate the geometric properties of L-beams for an optimum size and is included in the appendices. By performing a manual analysis of beams subjected to bending moments, a side length of 2 inches and a thickness of one-eighth inch were determined to have a factor of safety against fatigue loading of 1.42 using the Goodman line criterion [17].

A similar analysis was performed on the support beams for the walls and mounting device for the shock absorber, which are all under tensile and compressive loading only. To give a factor of safety of 1.5, the beams were determined to be one-quarter inch square.

4.3.3.3 Finite Element Analysis

During the structural analysis, there are two ways to test a complex design. The first approach is the traditional method, where a prototype is subjected to design loads, and an observation as to whether or not the model fails is made. New technology has made possible a second method of testing, computer modeling of structures called finite element analysis. This is well suited for the chassis design except that it will not consider thermal loads and stress concentrations.

By modeling the basic chassis design in a finite element software package, a the natural frequency for the chassis was determined. Three frequency modes were analyzed; one in torsion, one side to side, and one back and forth. The largest frequency was 0.705 Hz. Because the loading of the chassis at 10 km/h with a possible crater every 10 m, a resonance possibility is remote to vanishing. The undeformed and exaggerated deformations on the chassis are shown in Figure 4.1 . Appendix C.2 shows the finite element analysis results.

4.3.4 Additional Suspension Constraints

The struts of the double wishbone system will be constrained to have a maximum compression of twelve inches. Eighty percent of the travel of the struts will occur on a primary spring of constant 12 lb/in. The final twenty percent of travel will engage a secondary spring in the compound system with a spring constant of 100 lb/in. This is particularly important during night time operations where the cold temperatures increase the rigidity of the flexible wheels and thus the probability of bottoming out.

The vertical flexure of the wheels provide the spring constant in the suspension system as they permit a one and one-half foot vertical displacement. The control arms for the double wishbone suspension mounted on either side of the chassis and the hitches will protrude from the front and/or back. The suspension system is coupled with flexible hemispherical wheels.

4.3.5 Suspension Design

The double wishbone suspension allows independent vertical motion of each wheel. This keeps the tracking of the wheels in contact with the lunar surface to allow maximum use of the flexibility of the wheels in the suspension system. The struts' functions are to damp vertical deflections of the wheels, and prevent "bottoming out ".

Two dimensionally, the suspension system is a four bar linkage. The ground of this linkage is the side of the cart. Two triangular control arms are mounted to the side of the cart and allowed to rotate about the z-axis. These two arms are the same length and have the same orientation at all times. The fourth link is the spindle assembly (i.e. drive motor and steering servo).

The strut consist of a spring and damper system. The primary spring will compress 50 percent of it's travel for static equilibrium. Preventing damage to the vehicle, the secondary spring is used for occasional overloads and for protecting the suspension system from "bottoming out ". The secondary spring will not engage until 80 percent of the primary spring's travel is reached [20].

The operational loads were divided into two categories: frequent loads and infrequent loads. The operational analysis was performed by using a "design crater " of the lunar surface at a high frequency. The "design crater " has been chosen to be one meter in diameter because frequency of occurrence indicates a high probability of encountering this size crater. The spring mass model used in the load analysis is shown schematically in Figure 4.2 . Model constants and variable coefficients including wheel and spring characteristics are also presented in Figure 4.2.

The mathematical model considered three degrees of freedom: vertical translational motion, and pitch and roll rotational motion. Each of the wheels was treated as an independently suspended spring-mass-dashpot system using the schematic diagram shown previously in Figure 4.2.

Using DADS in 2-D the suspension system was modeled using the terrain as the design crater and a vehicle speed of 10 km/hr. The points of interest were: the peak vertical acceleration of the seats, the pitch acceleration of the seats and the time the wheels would spend off the ground. Results can be found in appendix C.3.

4.3.5.1 Material

The evaluation criteria considered strength at +/- 120° C, arc and resistance weldability, availability of extrusions and forgings, corrosion resistance, and cost. High strength Titanium alloys were not selected because of a higher cost of the material and increased manufacturing problems. The final system would have small

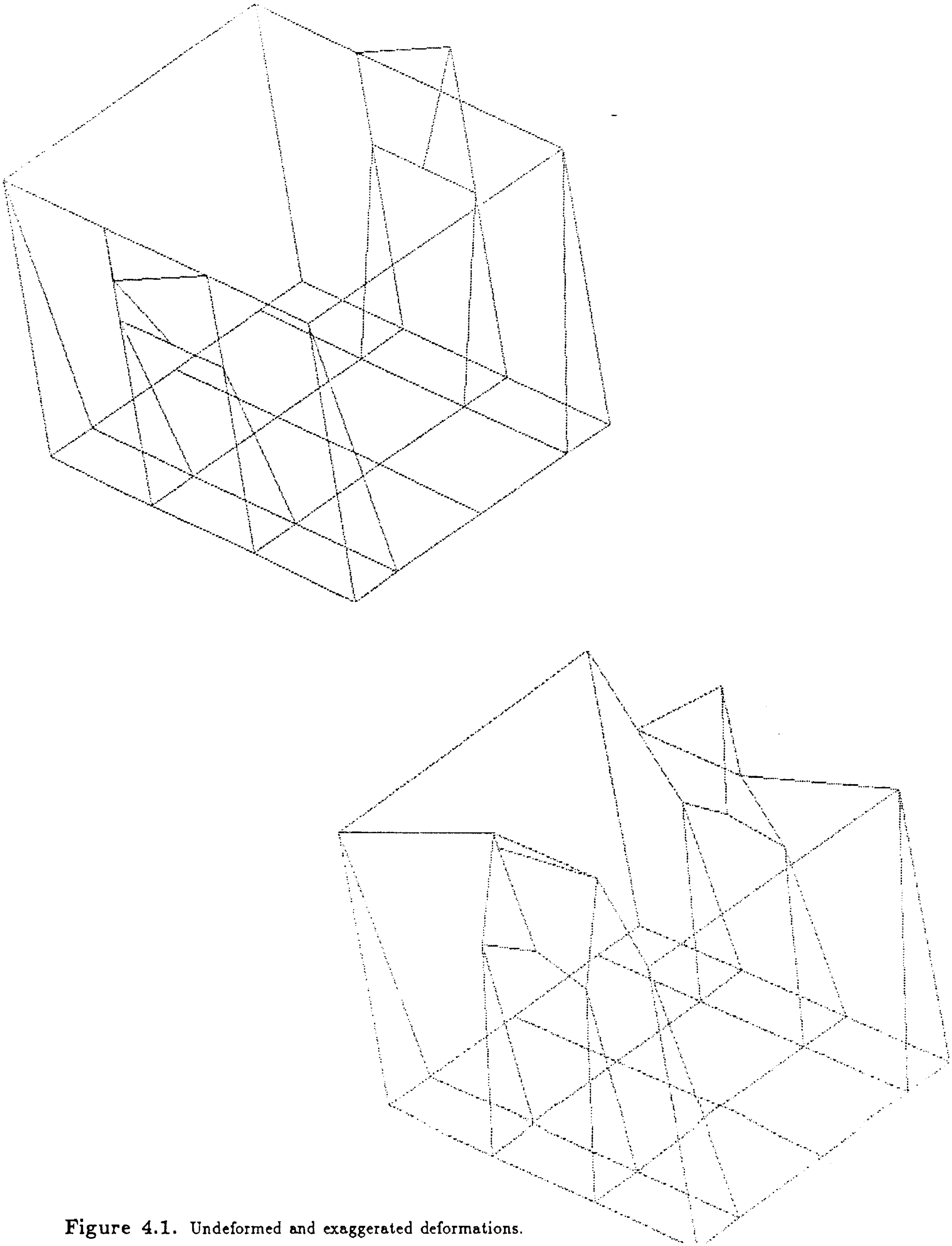

Figure 4.1. Undeformed and exaggerated deformations.

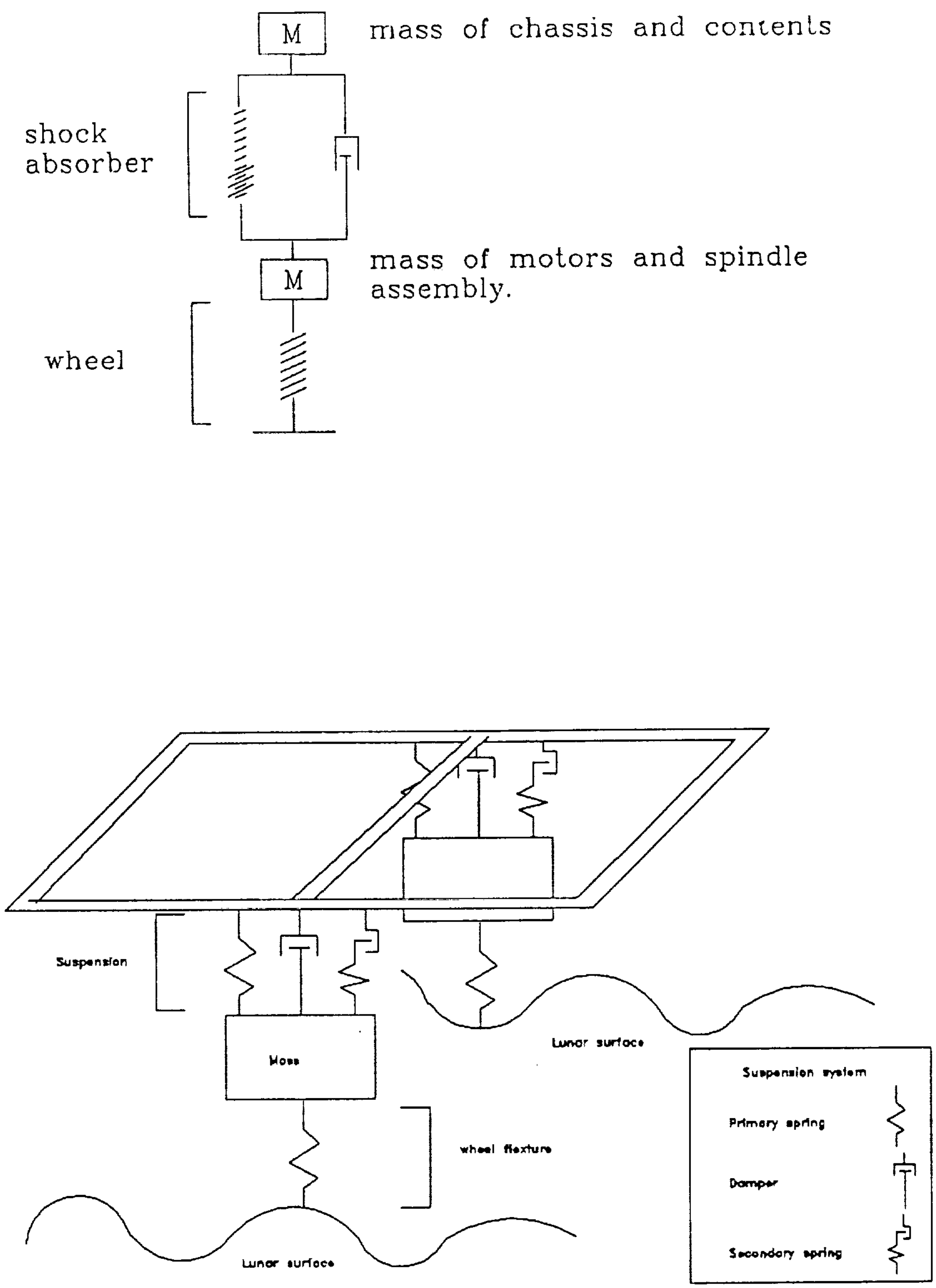

Figure 4.2. Suspension mathematical model.

weight savings in comparison to aluminum alloy but these savings do not warrant the additional cost associated with Titanium alloys. The magnesium alloys were not selected because of low strength capability and poor forming characteristics. The Wrought super alloys were considered (invar, Inconel 718, etc.) and discounted because of high costs and manufacturing difficulty. In the aluminum alloys, high strength alloys (7075 and 2024) were rejected because of poor weldability characteristics. Based on the previously stated criteria the best material for the job is square cross sectional tubing of aluminum 2219 [21]. Material evaluation for suspension is given in Table 4.1 .

The material selected for the frame was 2219 aluminum based on high weldability, high strength properties, and high fracture toughness. Comparisons of various other materials considered for the suspension system are shown in Table 4.2 .

The square cross sectional tubing was selected because it provides wire protection, has smooth surfaces (clean and simple structure), is available in standard size, and provides an efficient cross-section resulting in lightest weight configuration.

4.3.5.2 Spindle

The third component in the four bar linkage is the spindle assembly. This assembly houses the servo motors and steering mechanisms as well as serving as a mounting for the spindle plate. It is made of two parallel plates welded one on top of the other by connecting rods which keep them vertically aligned with each other. The connecting points to the control arms are therefore vertically aligned to keep a constant relative distance between the ends of the control arms and to maintain a vertical parallelogram.

A vertical plate is mounted on the outer face of the housing with its normal parallel to the x-axis. This plate, referred to as the spindle plate, has bearing blocks located at the top center and the bottom center to allow rotation in the x-z plane. Holes are drilled in the top and bottom plates to create the vertical axis, about which the spindle plate rotates. The hub of the hemispherical wheels is mounted on the spindle aligned along the x-axis. This hub is detailed under the wheels section.

4.3.6 Steering Design

4.3.6.1 Primary Steering

The steering is accomplished by electric servo-motors that rotate the spindle plate. Each wheel is turned by a separate servo that is controlled by the onboard computer. The steering servo is mounted to the housing and is connected to the spindle plate by a four bar linkage. When the servo is actuated it will rotate the first link which takes the rotational input resulting in a translational output via the second link. This in turn will push or pull the third link, or spindle plate. The spindle plate will then rotate about the y-axis created by the two sealed bearings located at the top and bottom of the spindle plate.

4.3.6.2 Secondary Steering

The secondary steering or backup system is an open loop on-off switch control operated from a power bus by means of a control stick or joystick. The power bus is wired directly from the steering servos through the joystick to the power source. It will bypass all onboard systems (i.e. onboard computers, monitoring and control devices) in case of failure. The joystick and power bus are located in the center of the forward bench seat and will allow operation from either the left or right side. Steering is accomplished by switching the power on and pushing the control stick in the desired direction of turning, left or right. Once the desired wheel angle is obtained, the stick is then returned to its center upright position.

This backup system is only effective for onboard system, wiring or communication failures. Because this vehicle has four wheel steering, if a steering servo fails the vehicle can be steered by a single cart. The steering servos for the damaged or affected cart will be locked in the forward position by an auxiliary pin which secures

Table 4.1. Material considerations for suspension.

Evaluation Criteria / Material Category	Typical Strength-to-weight ratio (10 E6 In) R.T.	120°C	As Welded joint Efficienay	Weldability Post weld Treatment Method	Final joint Efficiency (%)	Assesment
Wrought Super Alloys	.52	.51	50	Heat treat	90-100	Unacceptable. More difficult to work with and offers no strength advantage over aluminum alloys. Expensive
Titanium Alloys	.98	.86	80	Heat treat	100	Acceptable. Offers potential weight savings over Aluminum but tube availability is questionable. Good as-welded joint efficientcy.
Aluminum alloys 2021 2219 7075	 .59 .76 .58	 .59 .62 .52	50	Solution heat treat and age	89/67	Preferred. Adequate strength at temp excellent weldability. Tubes and forgings readily avalible. Low distortion quenching medium available if necessary to heat treat.
Magnesium Alloys	.51	.35	68	–	68	Unacceptable. Poor strength retention at 120° C, low maximum joint efficienicy, more suseptable to corrosion.

Table 4.2. Aluminum alloy suspension evaluation.

Alloy	Strength-to weight ratio		Weldability		Assessment
	R.T.	120°C	As welded joint efficiency (%)	Maximum joint efficiency	
2014-T6	.59	.53	Fusion welding not recommended. Special Technique required.	- - -	Unacceptable. Weld difficulties
2021-T81 2021-T62	.64 .66	.55 .53	50% 50%	Not known. Comparable to 2219	Acceptable. Comparable to 2219. Affords higher allowables than 2219 Particularly in weld yield strength May require testing to establish form design allowables.
2024-T81	.66	.62	Not fusion weldable	- - -	Unacceptable. Not fusion weldable
2219-T81 2219-T62	.59 .53	.52 .46	50% 50%	89% STA	Prefferred. Good weldability. Experience with as-welded using weld lands. Readily available. Applicable manufacturing processes.
6061-T6	.43	.37	50%	100% STA	Unacceptable. Low strength.
7075-T6 7075-T73	.76 .66	.62 .55	Not fusion weldable	- - -	Unacceptable. Not fusion weldable.
7079-T6	.74	.65	Not fusion weldable	- - -	Unacceptable. Not fusion weldable.
7178-T65	.77	.67	Not fusion weldable	- - -	Unacceptable. Not fusion weldable.

the steering linkage to the non-rotating spindle. This will be done by a handcrank that fits into the steering servo. Once the wheels are locked the cart with working systems will steer like a two wheel steering vehicle. The problem of complete steering servo failure (all four wheels) was not considered because it would be highly improbable.

4.4 Center of Mass

4.4.1 Center of Mass Description

It is very important to know where the center of mass is for each cart. This system is not a perfect case scenario, therefore, the center of mass for each respective cart will not be directly in the middle of the cart over the axle. This is because equipment is placed in various places in the cart. It is important to know exactly how far the center of mass is from the center of the cart so that it can be corrected by placing the same amount of mass in symmetry on the opposite side of the axle. These problems need to be ironed out before deployment to prevent catastrophes such as tipover, increased stress and strain, and decreased performance.

4.4.2 Additional Center of Mass Constraints

The center of mass of each cart will have an error tolerance to the center of geometry that varies dependant on the total mass of the vehicle. For a worst case scenario of a 1000 kg loaded cart, the range of c_M will be six inches in the Y-axial direction and two inches in the X-axial direction. The center of gravity of an assemblage of elements is found by a simple weighted averaging procedure. (In physics, the center of gravity is usually called the center of mass.) Beginning with any arbitrary reference point, the center of gravity is found by summing the products of the masses and x,y,z offsets of each element (the moments) and dividing by the total mass of all elements.

4.4.3 Center of Mass Calculations

The calculations needed to locate the center of mass of an object filled with many small objects were integrated into a Fortran program that computes the center of mass of each cart in the three cart LARTS, fully loaded with various objects of different size and shapes. The program also computes the distance from the axle that is needed to locate the spot where an equivalent mass shall be placed to balance the load. The program makes use of files to input information and output data in direct formatted style. It is also "to the point " and easy to use in order to expedite the process of transforming critical information into useful data. The program walks the user through each calculation by asking what to input and telling what will be outputted. The main body of the program is none other than the calculation of the center of mass of the cart loaded with objects. The x, y, and z coordinates are calculated from the basic equations listed:

$$\bar{X}\sum M = \sum \bar{x}M \Rightarrow \bar{X} = \frac{\sum \bar{x}M}{\sum M}$$

$$\bar{Y}\sum M = \sum \bar{y}M \Rightarrow \bar{Y} = \frac{\sum \bar{y}M}{\sum M}$$

$$\bar{Z}\sum M = \sum \bar{z}M \Rightarrow \bar{Z} = \frac{\sum \bar{z}M}{\sum M}$$

where $\bar{X}$, $\bar{Y}$, and $\bar{Z}$ are the world coordinate components being calculated, $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the local coordinate components of various objects, and M is the mass of the various objects. The coordinate system is defined as being three dimensional with the origin located in the left-rear corner of the cart. The width of the cart is given as being in the positive x-direction, the length is given as being in the positive y-direction, and the height is given as being in the positive z-direction.

As efficient as this program is, it does contain one drawback. It does not account for interference. This program is set up to handle simple shapes. If an object is introduced into the system that contains a protruding appendage, it might interfere with another object that has been placed nearby. The best way to handle this problem would be to model the system in a three dimensional analysis. This requires the use of programs such as CAEDS, SILVER, and IDEAS. These programs automatically check for interference. This modeling process is quite tedious and is not cost effective for this purpose.

4.5 Wheels

4.5.1 *Wheels Description*

The final design of the lunar rover wheels is depicted in the artist rendition of the complete vehicle. It is essentially a hemispherical shell supported on the inside by an array of geometrically curved ribs.

4.5.2 *Additional Wheel Constraints*

The wheels must overcome free motion rolling and bulldozing resistances from the lunar surface. In addition, the wheel material, susceptible to ultraviolet radiation and abrasive lunar dust, will need a protective coating on the shell, and a wear resistant contact track. The wheel must remain elastic in day and night operation (temperatures -240° to 220°F. The wheels must be design to avoid accumulation of regolith during normal operation.

4.5.3 *Wheels Design*

In order for the wheels to sustain the large temperature gradient between night and day, both the ribs and the shell will be constructed out of Kevlar 49. This material, however, is susceptible to ultraviolet radiation and will need a protective coating. The resistance to free rolling motion of a wheel is called rolling resistance. This resistance is increased as the surface area increases and when dealing with such a design becomes an important constraint. However, at the same time, the bulldozing resistance is reduced with an increase in surface area. In effect a trade off is made between the two critical resistance factors in the attempt to maximize traction, flexibility, and light weight. The wheel diameter of 2.3 m (7.5 ft) was chosen to optimize the load carrying capacity and yet not exceed power requirements. A minimum tread width of 0.31 m (1.0 ft) will allow plenty of surface area for good traction. The rib array allows self reshaping of the shell and has the ability to dampen any sudden shocks. Refer to Figure 4.3 for the wheel design.

4.6 Hitch

4.6.1 *Hitch Description*

The concept of using a succession of individual carts having only one axle proposes the problem of how to keep them attached and level at the same time. The hitch is illustrated in Figure 4.4 .

4.6.2 *Additional Hitch Constraints*

The degrees of freedom constitute the major constraint in the hitch design. While the rolling motion takes place between the second cart and the shaft, the pitch and yaw motions take place at the ball and socket joint on the first cart. The orientation, or line of action, of the springs must be such that the motion of the ball and socket causes pure compression of the spring. In addition, the springs must have different spring constants for

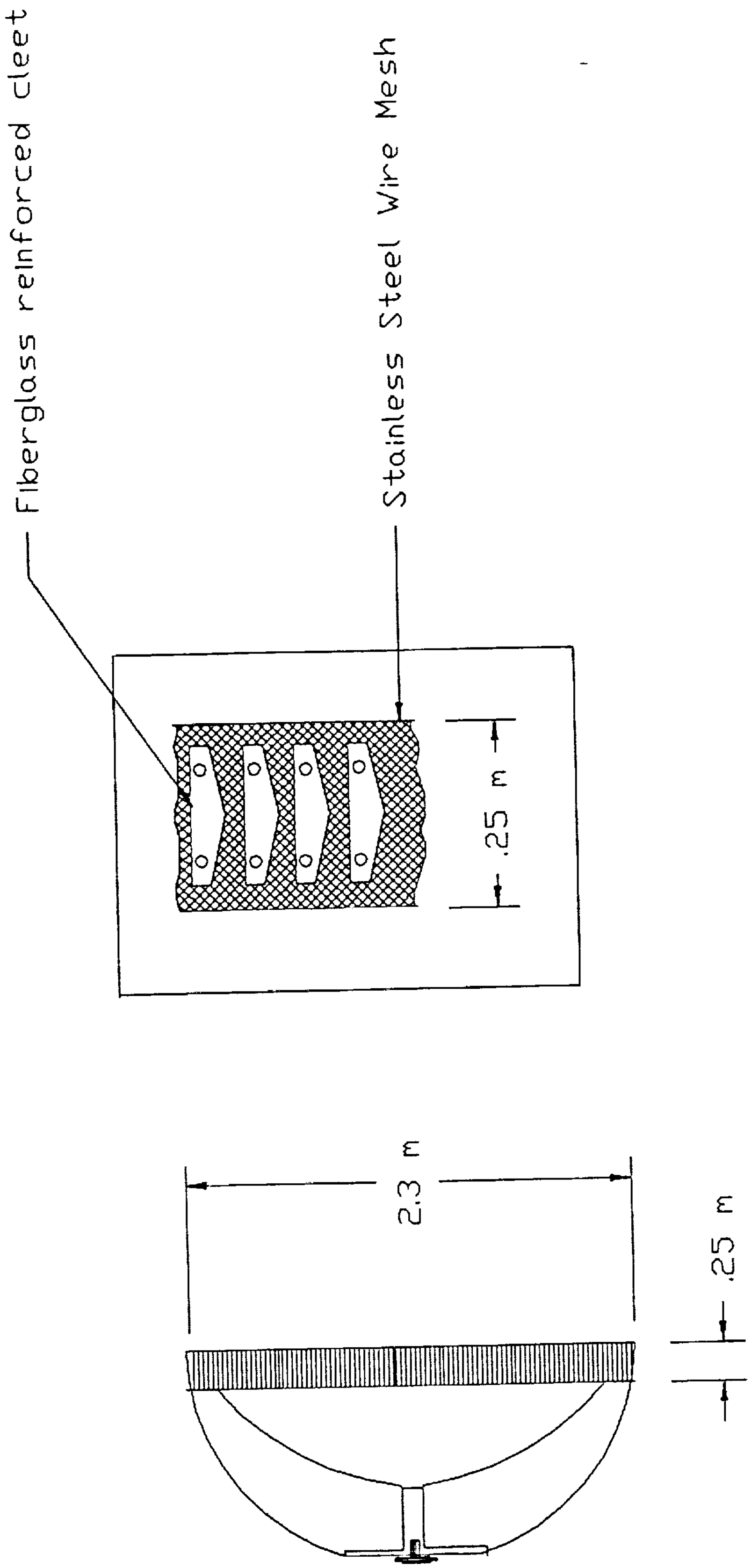

Figure 4.3. Wheels design.

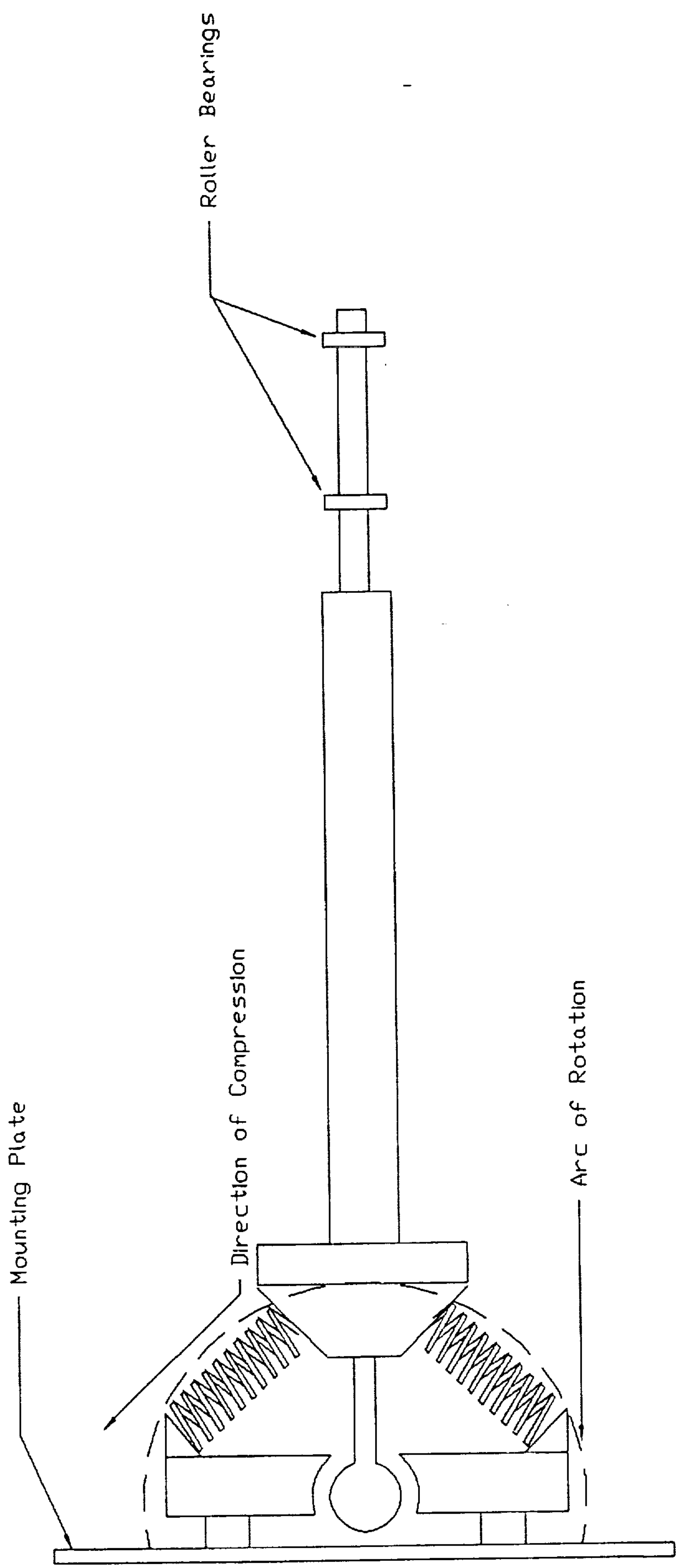

Figure 4.4. Hitch design.

two loading scenarios: 1) the vertical springs must be designed to balance moments caused by a displaced c_M as determined by the Center of Mass Constraints, plus a 200 Earth pound astronaut boarding the passenger cart. 2)the side springs must not cause skidding of the carts during a turn. Note that if the first two carts are in a turn to the right, then the starboard springs will be in compression and port side springs will be in tension and vice versa, so the spring constant is one half for each spring.

The motion of the hitch has to allow for 30 degrees of yaw, turning, in the horizontal plane between consecutive carts. In addition, it must allow for a maximum of 25 degrees pitch in the vertical plane and a final constraint of 45 degrees roll between carts.

4.6.3 *Hitch Design*

The first two carts are the critical links in the LARTS design. By providing the desired motion and maintaining a level ride for them, any number of additional carts can be added using a conventional hitching system. To emphasize the point, a car or truck on earth is a four wheel vehicle and offers enough support of its own to add a trailer. With the LARTS the first two carts must simulate a four wheel vehicle and still remain flexible at their connection.

The necessary movement is taken care of by the use of a ball and socket joint. The socket is rigidly attached to the back of the second cart. The shaft extending from the ball is mounted on a series of two bearings on the second cart. The pitch and yaw motions take place at the socket joint on the first cart while the rolling motion takes place between the second cart and the ball-shaft. This division of motion among the hitch components is necessary to keep the ball-shaft from spinning inside the socket. This allows the spring mechanism means to attach to both the hitch and cart providing the most important constraint, level ride.

The spring mechanism is an array of eight coil springs mounted concentrically about the socket joint. Each spring has one end mounted at the first cart and the other on the ball-socket. If, for instance, the first two carts are in bending, then the upper springs will be in compression while the lower springs will be in tension. If the first two carts are in a turn to the right then the starboard springs will be in compression and the port side springs will be in tension. The springs must not all have the same spring constant. The side springs must not be so stiff that they cause skidding between carts during a turn.

The orientation, or line of action, of the spring must be in such a way that the motion of the ball-socket causes pure compression of the spring and no deformation in bending. This can be done by positioning the socket joint at the center of the spring array so that in effect the ends of the springs are mounted to a spot inside of the first cart just beyond the location of the socket.

4.7 Seats

4.7.1 *Seats Description*

The seats of the LARTS will be a bench style. This enables easy entry and exit of the vehicle.

4.7.2 *Additional Seat Constraints*

The seats are to provide adequate positioning of one or more astronauts at a time. In addition, they must also be easy to get in and out of so the astronaut can perform his mission without expending extra energy.

4.7.3 *Seat Design*

The bench type seat was chosen to accommodate either one or two astronauts. If only one uses the LARTS he can position himself in the middle of the bench to balance the cart. Because the actual size of the bench is dependent on the size of the Hard Space Suit the dimensions have been omitted. Today's automobile seats are designed in such a way that the body's position aids in its own constraint to the seat. For example, in many sports cars the bottom seat in contact with the legs is raised at an angle in the front. This is so that any transfer of the body's weight will be resisted by this part of the seat rather than just allowing the body to slide off. These types of designs rely on the passenger to expend extra energy while getting in or out.

This is not the case with the LARTS. Any extra expenditure of energy will cause greater fatigue of the astronauts and lower his overall performance. The bottom is constructed of a lightweight diamond grill made of aluminum to provide good support. A cushion will be used to dampen the transfer of shocks between the astronaut and seat. The bottom will have an orientation parallel to the floor of the cart with the back angled clockwise 10 degrees from the vertical. Short straps that attach to both sides of the hip and at both knees of the space suit will provide the best seat constraint while the LARTS is in motion. The idea of a lap belt was discarded because they would not aid in the positioning of the astronaut in his seat. The length of the lap belt would cause a problem for the astronaut to get control of the end to make connection. A foot rest will also be placed at the proper distance offering the astronaut the ability to rest his feet. Access to the LARTS will be done at the front of the cart. A step ladder will swing into place offering support between the ground and cart. This will keep the cart from rocking forward and causing the astronauts to fall out. Once in the cart the step ladder can be drawn back into its original position.

4.8 Conclusion

4.8.1 Chassis

The chassis of the carts on the LARTS is a rectangular box in shape with a total mass of approximately 25 kg (55 lbm). The structure will support the loads as determined by the contents of each vehicle. The supports that are greater than four feet in length will be L-beams in order to protect against bending. The floorboard will be made from a honeycomb insert layered on both sides with thin aluminum plates. Additional support for the heavy loads on the third cart will be supported by triangular support trusses.

The suspension system is composed of double wishbone vertical struts coupled with flexible hemispherical wheels mounted on either side of the cart. The double wishbone suspension consists of three links, an upper control arm, a lower control arm and a spindle assembly, that form a vertical parallelogram with the side of the chassis. The spindle is the housing for the drive system (i.e. motor and steering), and a mounting for the wheel. The total effect of the suspension system is to damp out vibration created by driving over the crater filled lunar surface.

4.8.2 Center of Mass

The center of mass of an assemblage of elements is found by a simple weighted averaging procedure which involves the division of moments by total mass. Calculations needed to locate the center of mass is integrated into a user friendly fortran program, which makes use of files to input information and output data in direct format style.

4.8.3 Wheels

The LARTS wheels are 2.3 m (7.5 ft) in diameter and 0.31 m (1.0 ft) minimum in tread width. Essentially, each wheel is a hemispherical shell supported on the inside by a polar array of geometrically curved ribs. This particular design offers a large ground contact area to provide adequate traction on the lunar surface. Furthermore, a trade off is made between the rolling and bulldozing resistances to maximize traction, flexibility, and weight characteristics.

4.8.4 Hitch

Figure 4.4illustrates the configuration of each component of the hitch with respect to the first two carts and every other component. The ball and socket and spring mechanism should prove satisfactory in providing the necessary motion while at the same time keeping the first two carts in a level position. The hitch attaching the second and third carts is similar to hitch designs today.

4.8.5 *Seats*

The seats of the LARTS will be of bench design. Besides accommodating comfort and easy access, the seats provide a means of center balancing the front cart. Hip and knee short strap belts, as well as foot rests, help constrain the astronauts, while prohibiting the expenditure of excess energy. A step ladder will swing into place offering support between the ground and cart in accessing the bench seats.

5. EVA/Crew Stations

5.1 Introduction

The EVA/Crew Stations system consists of EVA suits, the display console and system integration, scientific tools and equipment, and the steering mechanism. It is important for the EVA suits to be fully functional with an EC/LS system to permit locomotion and life support. The display console is completely visible at all times. The steering mechanism is easy for the astronaut to use, as the gloves are bulky and thick which limit the hand movement. Finally, the astronaut will have useful tools to perform scientific experiments and gather soil samples. Scientific tools and equipment are addressed in appendix D.1.

5.2 Constraints

Since the Lunar ARTS is to be electrically powered, the power consumption of any display system must be considered. The display system must provide a means of ease of visibility without causing a distraction to the astronaut. The tools and equipment as well as the Main Regolith Compartment Bags must be attached securely to the aft pallet assembly and tool carrier mainly because they ride on the outside of the third cart. The EVA suits must provide life support for the astronauts during the lunar missions. The steering mechanism must be easy for the astronaut to operate, since the gloves attached to the EVA suit are large and bulky and not capable of a gripping action.

5.3 EVA Suits

5.3.1 Description

The Extravehicular Mobility Unit (EMU) is an independent anthropomorphic system that provides environmental protection, mobility, life support, and communications for the astronaut to perform Extravehicular Activity (EVA) in Earth orbit. EVA is defined, for EMU design considerations, as any time the EMU external environment pressure is below 4.0 psia.

A human needs artificial pressurization above 12 km (40,000 feet). The beginnings of space suit technology can be traced back to the 1930s and Wiley Post's high-altitude suit for aircraft. Emergency high-altitude suits were developed by the military after World War II. A true space suit, however, must do more than predecessor aircraft suits. It must offer some degree of full-body mobility and should provide a self-contained environmental control and life support (EC/LS) system so that an oxygen-carrying umbilical is not needed. Body heat must be evenly removed from the entire body and rejected to space.

By the mid-1950s the Air Force had developed a partial pressure suit that sufficed to keep an airman alive in a high altitude emergency until the aircraft could be brought to lower altitude. By 1959, the Navy had developed a full pressure suit that was the technical precursor to the space suit used on the Mercury space flights. The Gemini suit was a full pressure suit with better arm and leg mobility and was the first American suit actually used for EVA, with Ed White's 20-minute "spacewalk" on Gemini 4. This suit did not have a portable EC/LS life support system and was connected to the spacecraft by an umbilical which kept the suit purged with oxygen. The suit operated at about 24 kPa (3.5 psi); metabolic heat was removed by sweat evaporation from the skin. This suit proved poorly suited to EVA work. The visor, for example, fogged up when a crewperson was working hard. Sweat evaporation did not work well because the oxygen purge was uneven.

The Apollo suit had to be a fully functional space suit to permit locomotion by walking on the lunar surface. It had a portable EC/LS system capable of supporting EVA for about 8 hours with some margin. A liquid-cooling inner garment was first used on the Apollo suit and worked well. This garment covered the entire body except for head and extremities, was in contact with the skin for heat removal, and was made up of nearly continuous networks of small tubing through which flowed a coolant liquid. The coolant temperature was adjustable. The Apollo suit also operated at 24 kPa on pure oxygen. Carbon dioxide was removed by LiOH canisters. Heat was rejected by water evaporation, about 0.5 kg (1 lb) per hour at typical EVA metabolic rates, equivalent to moderate exercise.

The Skylab suit was a derivative of the Apollo suit, but did not include a portable EC/LS system as all Skylab EVA was planned and conducted adjacent to the vehicle so that umbilicals were practical. EVA was extensively used on Skylab for planned mission activities as well as for unplanned ones. The latter saved the mission, beginning with the solar wing repair and sunshade on the first crew visit. The Skylab missions had more unplanned than planned EVA hours.

The shuttle suit is a new design with improved mobility and a new portable EC/LS. The Shuttle suit is similar in most respects to the Apollo suit. Subsystem functions are generally the same. Unlike the earlier suits which were individually tailored to each astronaut, the Shuttle suit is modular with a range of sizes for its parts such as arm and leg sections, and means of adjustment. Thus a Shuttle suit can be fitted to the crewperson by selection of appropriate part sizes and by adjustment.

All of these suits have employed similar design philosophy; they employ fabric design for the movable joints. The Shuttle suit uses a hard upper torso. Its shape is elliptic rather than cylindrical in cross-section, providing more useful work area for the crewperson's hands in front of the chest.

A number of years intervened between the last Skylab EVA and the first EVA on Shuttle. During this period an attitude developed on the part of some space engineers that EVA should only be used as an emergency measure. It was as if people had forgotten how routine it was on the surface of the Moon. The Solar Max repair and satellite retrieval missions with Shuttle have all but dissipated that attitude and EVA is now regarded as a routine operation for space station mission planning.

5.3.2 Additional Constraints

Currently, the new technologically designed hard space suit has the ability to operate at 8 psi. for a duration of 8 hours. For the entire duration, the average metabolic rate may not exceed 1000 Btu/hr. The oxygen tanks contain 2.6 lb. of oxygen at 5800 psia. and deliver between 3.33 and 3.9 psia. depending on the flow rate. The Shuttle cabin operates at a much higher pressure of 14.7 psia. To avoid aeroembolism when going from Shuttle cabin pressure to suit pressure, a crewperson must breathe pure oxygen for about 3 hours, to purge nitrogen from the blood and body tissues. On recent missions, the shuttle cabin pressure has been gradually reduced to about 9 psia. prior to EVAs to reduce prebreathe time and risk of bends. The large difference between cabin suit pressures is a serious operational problem, and a suggested remedy is the use of a higher suit pressure. At present, as previously mentioned, 8 psia is representative of the design pressure for future suits. Experimental hard suits have been operated at this pressure in tests.

5.3.3 EMU (suit) Design Considerations

In this section, an EVA suit that will adapt to the Lunar ARTS Vehicle is proposed. The suit needs to be compatible to the seat design and fabrications need to be introduced to allow integration of the seat belts.

The modern technology of today is represented in the area of EVA suits by a hard suit as opposed to the modern soft suits presently used on the Space Shuttle. Hard suits have tended to be somewhat larger and heavier than fabric soft suits, but future developments are expected to reduce this difference. A hard suit is more mobile than a fabric suit and can more easily be fitted with radiation shielding since the external surfaces are rigid except for the joints. Another advantage of hard suit technology is increased life. A space station suit needs to be capable of at least dozens and preferably hundreds of uses without major refurbishment.

The typical hard suit (Figure 5.1) joint is a toroidal convolute elbow joint, Figure 5.2 The joint design principles for hard suits have not been applied to gloves, and may not be because of the small parts size that would be necessary. Volume compensation in gloves has been incomplete. The effort required to close one's hand in a glove under pressure is fatiguing on long EVA sessions involving a of hand work. The problem gets worse at higher pressures but can be compensated by better glove design. Final selection of a new suit pressure must

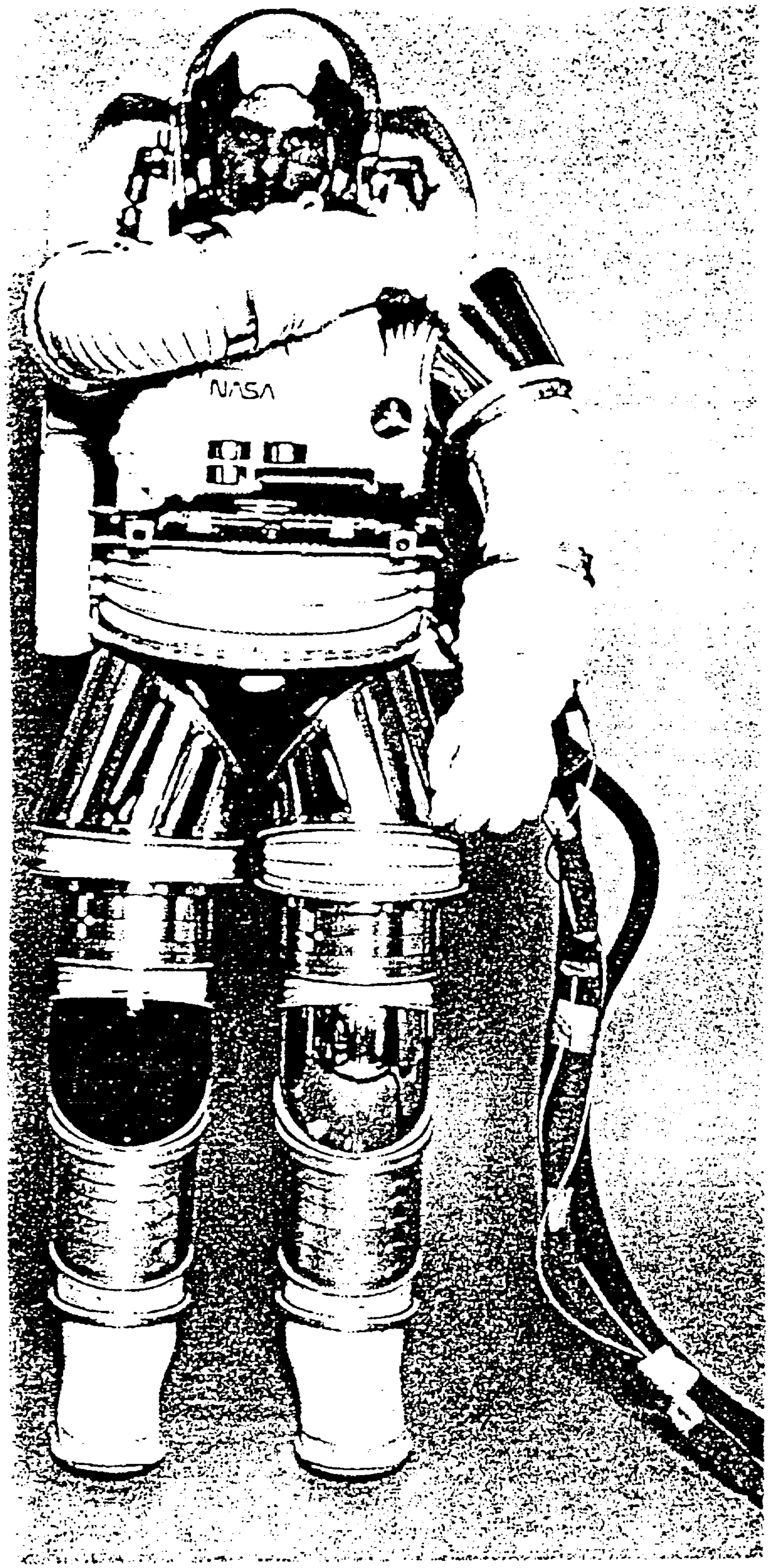

Figure 5.1. EVA Hard Suit.

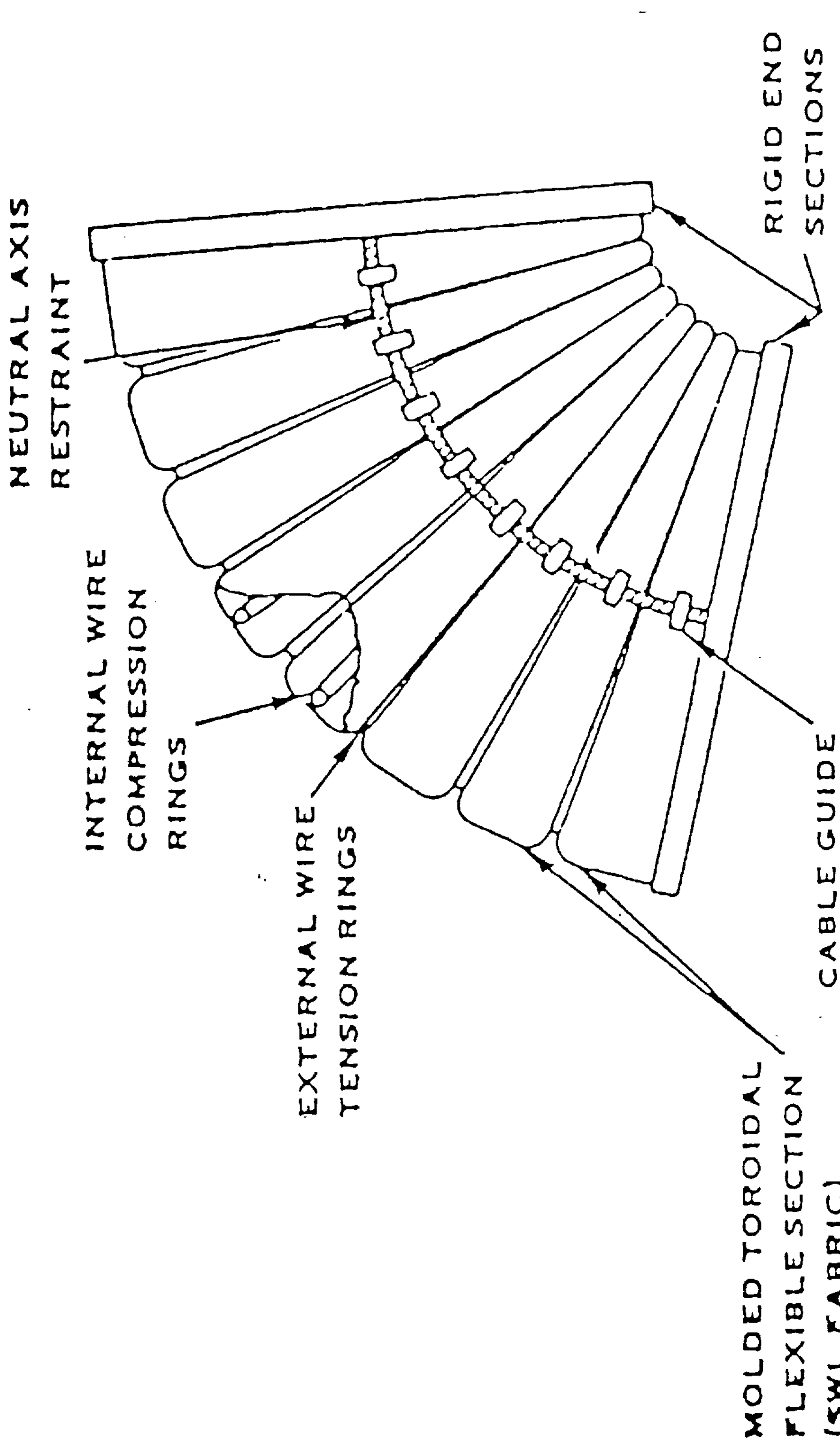

Figure 5.2. Toroidal convolute elbow joint.

consider adequate glove mobility as well as cabin pressure and how much lower suit pressure can be without risk of bends.

The optimal design for attachment of the seatbelts to the hard suit is a set of aluminum rings with an ID of 1.5 in. and an OD of 2.0 in. The rings will be mounted on either side of the astronaut's waist and the seat belt clamps can be hooked in securely. Another set of rings will be attached to the knees to keep the astronaut from falling backward in the seat when traveling over rough terrain.

5.4 Display Console

5.4.1 Description

On the previous lunar expeditions one of the problems that arose was the inability of the astronauts to clearly see the display information presented on the Lunar ARTS due to lunar dust. It is of the utmost importance that the astronaut be able to clearly see his display information at all times. It was, therefore, necessary to design a system to solve these problems.

5.4.2 Additional Constraints

Since the Lunar ARTS is to be electrically powered the power consumption of any display system must be considered. The display system must provide a means of ease of visibility without causing a distraction to the astronaut. A more detailed explanation of the operations of the Display System can found in Chapter 6, Section 3.

5.4.3 Display System

In the display of information the astronaut must be able to call up various selections of data as needed for the completion of the mission goals. This could range from Lunar ARTS system information to scientific tools information status.To accomplish this task the display system must easily integrate with not only the Lunar ARTS systems but also with the numerous instruments and vehicles that could be put into use on various systems. To accomplish all of the desired functions, it was decided that an inner-helmet device be used. This device consists of a fiber optics system that displays its information on a holographic medium. The display of information is accomplished in the following manner, an holographic film is placed within a 30 degree radius of the astronauts right eye. This film is where the information is projected. The astronaut sees the information projected at infinity, this means that the information would seem to be floating in space. This is accomplished by the projection of the display information on the holographic film in the front of the right eye. When the brain sees this image it superimposes it on the image that the left eye sees, this gives the astronaut the sense that he is only seeing one true image. The display system contains no high voltage supplies and is totally fiber optic. This is preferred in that there is little power drain and exposes the astronaut to no high voltages. Since the display system is simply a means of displaying information it may act as a display for other instrumentation as well. In the case of a helmet failure a backup hand held display could be plugged into the system to take the helmet display's place.

5.5 Steering Mechanism/Hand Controller

The hand controller is a "joy-stick " type element providing drive (forward, reverse), speed, and directional(left, right) control to the Lunar ARTS drive system.

5.6 Summary

The EVA/Crew Stations system is a very important part of the Lunar ARTS vehicle, considering the fact that if the system cannot be manned, the only other way to operate it would be by remote control. Space science has come along way since the first Apollo mission, and technology continues to advance, paving the way for future journeys into the vast unknown of space travel.

6. Navigation and Communications

6.1 Introduction

The object of the navigation system (Figure 6.1s to direct and control the movement of the Lunar ARTS from one lunar base to another, or to any point in between. In designing the system many factors concerning and relating to this purpose must be taken into consideration. Not all can be addressed here so we will deal mostly with a description of the system, and how some of these factors relate to the system.

Every control aspect of the Lunar ARTS incorporates communication systems (Figure 6.2). These systems transmit various signals including voice, data, video, and control signals. All of these signals assist in the navigation of the vehicle. The following sections suggest processing and modulation schemes best suited to each of the information types. In optimizing the design, each discussion considers minimizing conversions and reducing noise effects.

6.2 Constraints

The lunar environment dictates the materials of electronic equipment. Lunar radiation affects the performance of the electronic component. For this reason, the design necessitates the use of radiation hardened components. These components reduce the noise caused by radiation. The environmental effects of temperature also create undesirable effects in the transmission of data. Therefore, not only must the components be radiation hardened, but should be relatively temperature insensitive through a broad range of temperatures to produce predictable electronic systems. Aside from component considerations, solar effects on radio waves need be reduced. Through the use of relatively high carrier frequencies, such effects can be minimized.

The navigation system of the Lunar ARTS is required to enable the user to have remote or manual control of the vehicle. It will have the ability to determine precise distances of nearby objects for remote operations. It will have the ability to send three dimensional images to a remote station along with relevant parameters such as velocity, fuel level, and distance to target object. It also will employ a heads up display (HUD) and Inter-Helmet Optical Aid (IHOA) inside the astronauts helmets.

6.3 Navigation

6.3.1 Description

The core of the system is the central processing computer located at the lunar base. In normal operation it will co-ordinate and prioritize system functions. A less comprehensive back-up system will be operational on the cart. Another key element of the system is the Heads Up Display (HUD), a device much like the ones employed in jet fighters today. It serves as the primary link between the pilot, the Lunar ARTS, and the lunar base. A stereo vision system provides a three dimensional image for the pilot. A computer grid map of the lunar surface, in conjunction with the relay antennas (Figure 6.3 and Figure 6.4), enables precise point to point navigation. In designing subsystems, emphasis is placed on minimization of mass and power requirements on the Lunar ARTS, consolidation of as much hardware as possible at the lunar base, and maximum utilization of cutting edge technology.

6.3.2 Modes of Operation

There are three different modes of operation; on site, remote, and programmed. The primary mode is on site. In this mode the pilot is with the Lunar ARTS on the mission, connected to and controlling the Lunar ARTS via the HUD. At any time the pilot may elect to control the Lunar ARTS manually, and be guided by the lunar base or by eyesite. The remote mode consists of the pilot using the HUD to operate the Lunar ARTS from the lunar base. The HUD provides a visual environment that is indistinguishable from on site operation. This

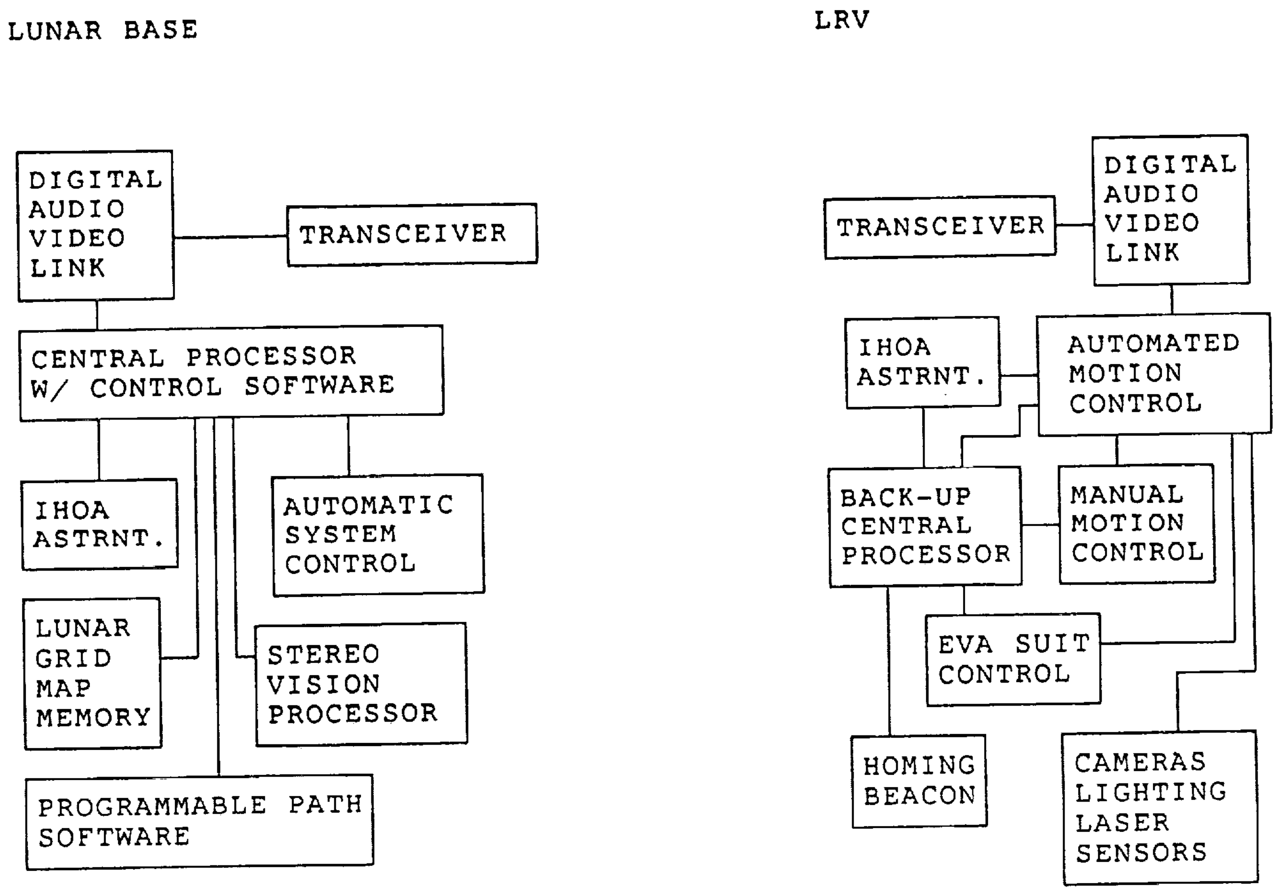

Figure 6.1. Object of the navigation system)

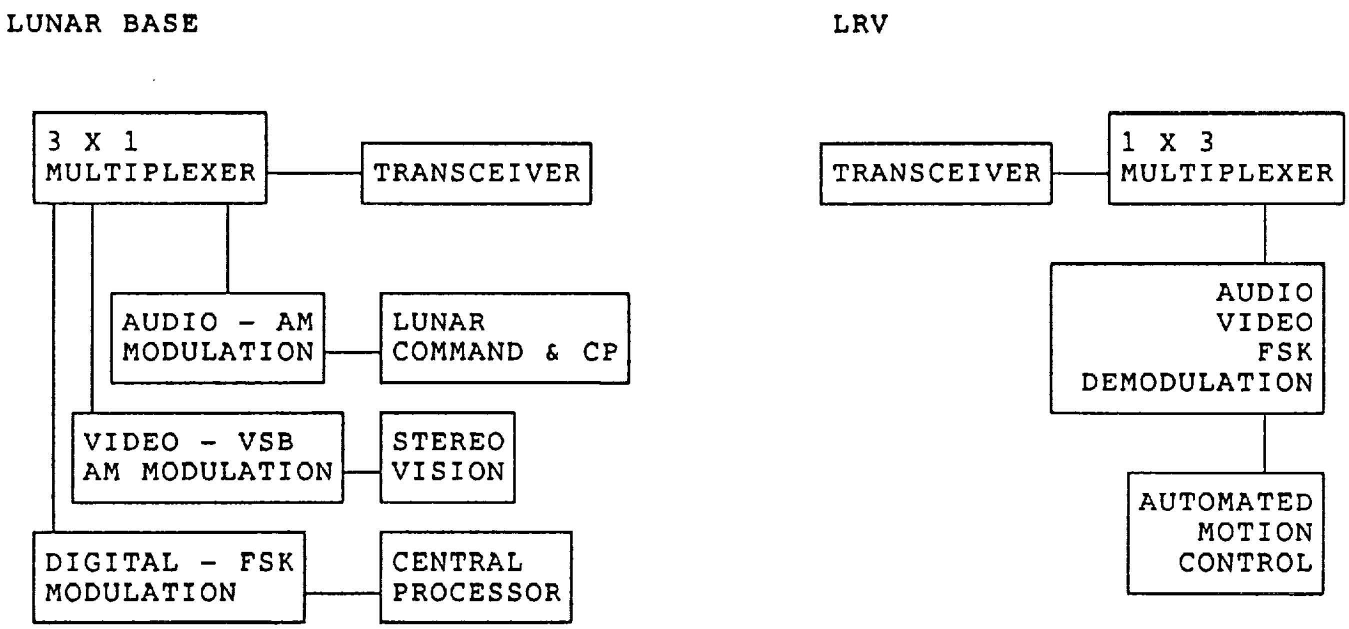

Figure 6.2. Luanr ARTS communications systems.

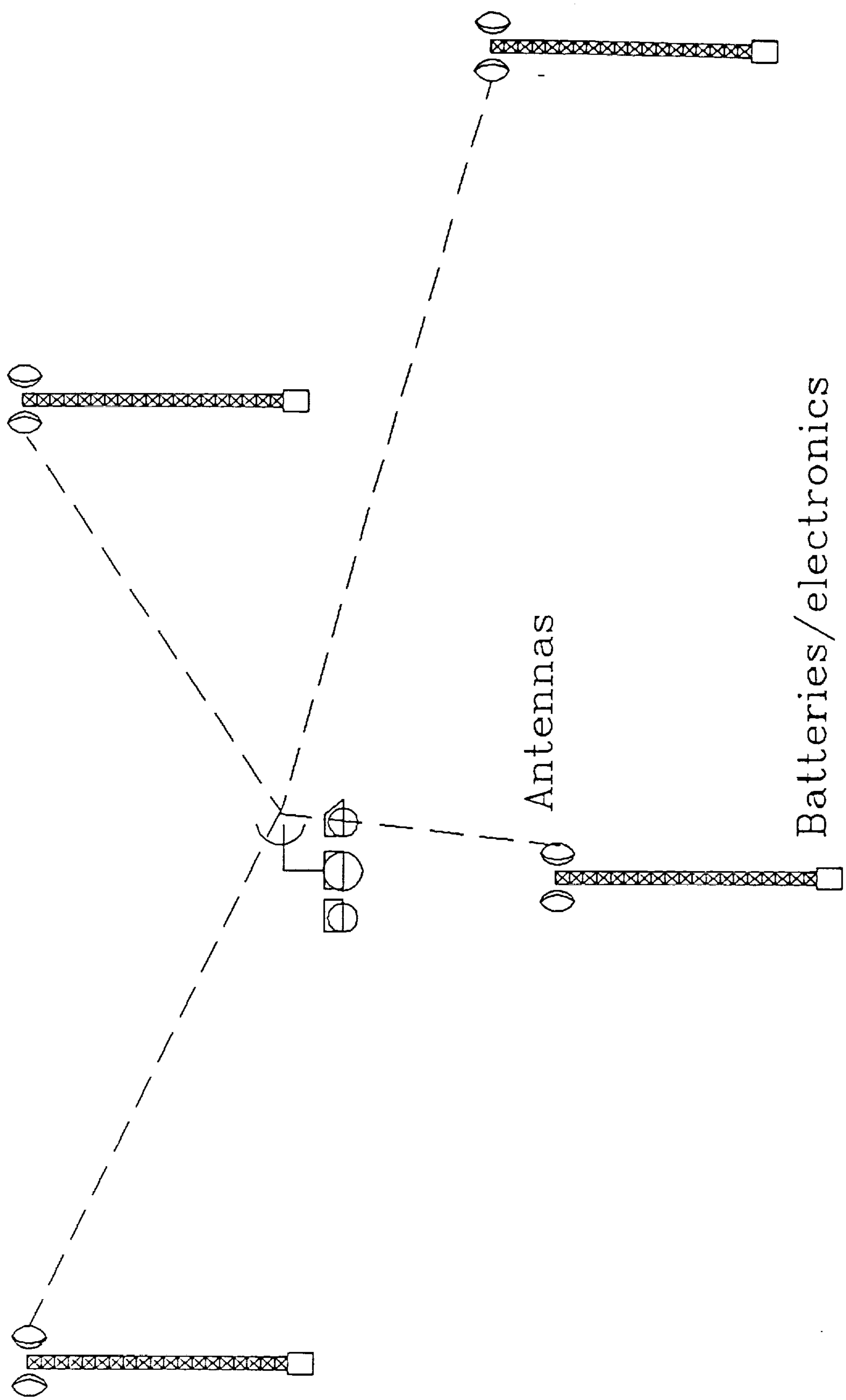

Figure 6.3. Computer grid map of the lunar surface.

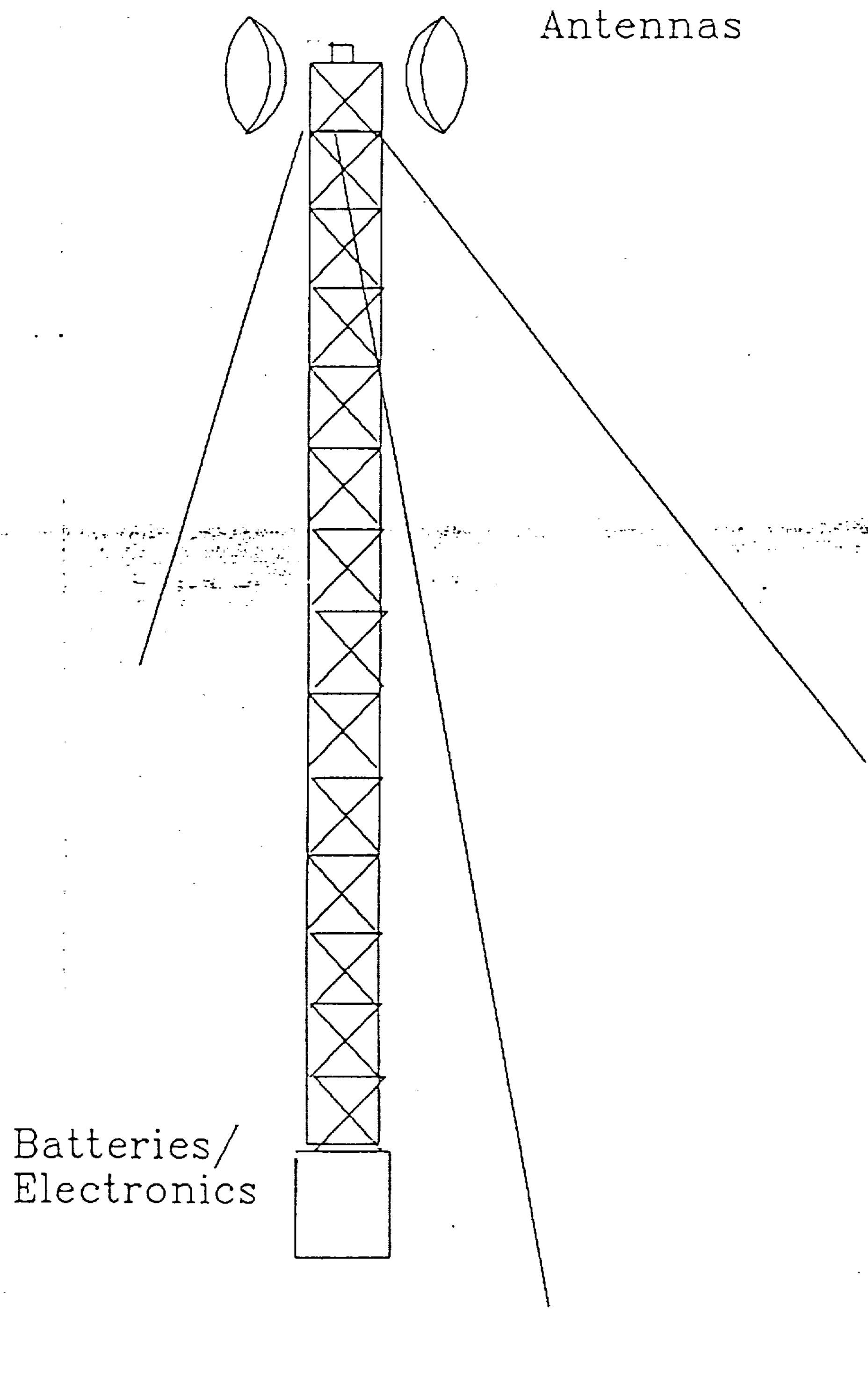

Figure 6.4. Relay antennas.

mode is useful for missions where a human presence is not necessary, or the on site pilot is unable to operate the Lunar ARTS. The programmed mode consists of the central processor control operating the Lunar ARTS from software, normally without direct human intervention. It is capable of real time adjustment to changing mission conditions. It relies on a grid map whose grid points are the locations of the communication relay antennas. A path can be learned and stored for later use. The HUD can be used in parallel to monitor the mission or for minor intervention. This mode is most often used for routine missions like resupply and raw materials transfer.

6.3.3 *Helmet Control*

This is the second most important component of the navigation system. It is a helmet worn by the astronaut that incorporates most of the control capability. All audio communication between the astronaut, co-pilot (if applicable), and the lunar base is routed through and controlled by the HUD. The stereo vision image is projected on the face screen as well as all pertinent mission signals. These include: mission time elapsed; mission time remaining; radiation exposure; external temperature; rate of fuel consumption; fuel consumed; fuel remaining; velocity; mission distance travelled; roll angle; pitch angle; compass heading; is stereo vision display activated?; is Lunar ARTS under manual, remote, or computer control? All control commands are voice activated and driven. It will be possible for the astronaut to call up or delete any of the control messages projected on the HUD screen (Figure 6.5). Anticipated advances in memory density, artificial intelligence, and neural networks make voice activation and recognition possible. The stereo vision image is of the immediate terrain or environment sensed by the cameras. The astronaut can use just the three dimensional image, or the actual environment as well. The HUD is a direct interface between the astronaut and the central processor computer.

6.3.4 *Stereo Vision*

Several varieties of stereo visioning systems exist. The most developed one uses triangulation to provide information concerning depth, but this is not as useful at long ranges or when high resolution is required. The Lunar ARTS employs a combination of triangulation and laser range finding. The information gathered by these two systems are combined by a computer to produce a three dimensional image. Problems presently exist with using a laser to provide minute depth information due to scattering, very weak return signals, and the need for broad area depth information. The broad area problem can be overcome by a scanning process, and intricate filtering schemes can be employed to receive and use the weak returning signal. The Lunar ARTS carries the cameras and laser, and sends the signals back to the lunar base to be processed. The three dimensional video image is returned to the Lunar ARTS and displayed in the HUD. This image is most useful in the remote mode. The camera, laser, and lighting are mounted on the front of the lead cart. They are conFigured either to move in conjunction with the HUD, to be controlled independent of the HUD, or to be stationary. A second positionally adjustable camera can be mounted at the back of the second to cart to provide monitoring of the cargo and assist in loading it in remote mode.

6.4 Communications

6.4.1 *Description*

Voice and video signals sent between the cart and the base utilize the standard practices for transmitting such signals. However, the other signal types require a more specific design. The data signals, transmitted from the cart to the base, transmit sensor values through analog FM signals. When reaching the base, a computer processes the data signals. Control signals, sent from the base to the cart, incorporate a digital FM transmission. Special byte-size codes induce the desired changes.

Velocity: ___
Mission Distance:___
Roll Angle:___
Pitch Angle:___
Heading:___

EVA Suit
Warning
Symbols

Mission Time
Elapsed:___
Remaining:___
Radiation Exposure:___
External Temperature:___

Field of Vision

Display Activiated:___
Manual Control:___
Remote Control:___
Computer Control:___

LRV
Warning
Symbols

Rate of
Fuel Consumption:___
Fuel Consumed:___
Fuel Remaining:___

Figure 6.5. HUD screen projection.

6.4.2 *Voice Transmission*

Although FM transmission produces clear signals, amplitude modulation (AM) produces a clarity in the transmitted signal widely acceptable for voice transmission. The amplitude modulation transmitter encodes the message signal in the amplitude of the carrier signal, a standard, high-frequency sine wave. In studying the frequency response of voice signal, few frequencies are found in the near zero range. Therefore, a single side-band (SSB) scheme for transmission is desired. In using SSB transmission, advantages include conservation of bandwidth as well as reduction the power consumption due to the suppressed carrier.

6.4.3 *Video Transmission*

Because stereo vision is incorporated in the design, two video signals need transmission. These signals, along with the data signal related to the range finder, present the required knowledge for processing the 3-D signal at the base.

Standard video transmission incorporates amplitude modulation for broadcasting. The recommendation for modulation is through vestigial sideband modulation (VSB) since, unlike voice signals, video signals contains a significant amount of low-frequency information. VSB modulation includes all the data of one sideband and part of the other sideband in its transmission. Thus, the transmission insures no loss in frequencies near zero and yet uses the same bandwidth as SSB transmission. In addition, the carrier signal should be included in the transmitted signal to aid in the detection and demodulation of the signal.

6.4.4 *Data Signals*

The base receives data from sensors on the cart. The signals sent, use FM transmission with an analog scheme (as opposed to a digital scheme). Using these concepts presents two main necessities to the design. First, since frequency is modulated, the transmitter requires ac signals. Therefore, a V/F converter turns the dc voltage signal into an ac sine wave, representing the frequency as opposed to amplitude. Later, the receiving device incorporates a F/V converter to retrieve the original analog signal.

In addition, since more than one parameter must be updated on the channel, the transmission system includes an analog multiplexer. This multiplexer, governed by a quartz clock, passes a predetermined order of parameters at set intervals. The multiplexer also sends null values to distinguish the various parameters from one another.

The analog signal requires a conversion to a digital signal for computer processing. An A/D converter accomplishes this task using an easily installed A/D card. Data processing, done by computer program, converts data from the input digital signal to useful information. For the computer to correctly read the data, the processing includes a sampling program that both determines the value of the input as well as recognizes the parameter currently being read.

Written in 8086 Assembly Language, the subroutine timings are calculated using the code and the clock cycle. Through the use of a null signal sent as an actual signal, the program determines the start of a new sequence of data. The transmitter also sends signals to assist in separating and centering each parameter.

6.4.5 *Base Control Signals*

To remotely direct the vehicle, control signals are an essential part of the design. Several types of control signals are to be sent such as speed, direction, and on/off power. Each signal type is to have its own identification byte sent in a bitwise, serial fashion. The signal triggers an incremental change in the desired parameter for each signal sent. Two identification bytes characterize direction (right/left movement) and speed (increase/decrease speed).

Another control orientated process involves HUD (Heads Up Display). The concept requires transmission of signals defining the angle for the cameras to be turned, determined from like movement of the navigators head. Each angle is specified by remaining identification bytes.

6.5 Communication Systems

6.5.1 *Voice Transmission*

Parameters necessary for the design of a AM transmission system include bandwidth (BW), carrier frequency (f_c), modulation factor (μ), and average power (S_{sys}). The bandwidth is chosen to be BW=3.4kHz. Next, a carrier frequency is chosen. Although commercial AM radio usually operates in the range of 0.535-1.605 MHz, the carrier frequency would be more acceptable in the area of 100MHz since solar interference necessitates the use of high carrier frequencies. Therefore,the carrier frequency is chosen arbitrarily to be 100MHz. A unity modulation factor is ideal, however, for practical consideration should be chosen at about 80 percent modulation. Finally, assuming a carrier voltage (Ac) of 5V,

$S_{sys} = \frac{1}{8}\mu^2 A_c^2 = 3.92$

A diagram of the SSB transmitter of Figure 6.1 uses a frequency discriminator. Note that the design incorporates a two stage approach because of the high sensitivity of the bandpass range (100MHz to 100.34MHz). Coherent detection demodulates SSB signals. Figure 6.2 outlines this simple detection circuit.

6.5.2 *Video Transmission*

6.5.2.1 *Parameters*

Video signals operate within frequencies of 0 to 4.2MHz. Adding the width of the vestigial sideband (f_r), the bandwidth becomes BW=5.45MHz. The large bandwidth dictates a carrier frequency chosen to be 20MHz. As far as power considerations, VSB consumes considerably more power because of the carrier frequency.

$S_{sys} = \frac{1}{2}A_c^2 + \frac{1}{8}\mu^2 A_c^2 = 28.42$

Therefore, both cameras together produce 56.84W.

6.5.2.2 *Modulation Scheme*

The block diagram of Figure 6.3shows the VSB modulation technique. The shaping filter, characterized by H(f), separates the SSB modulation from VSB modulation. Each shaping filter contains a unique transfer function dependant on the desired spectrum of the VSB signal.

Including the carrier frequency in the transmitted signal allows the use of envelope detection for demodulation as shown in Figure 6.4 where

$R_s << \frac{1}{f_c} << R_l << \frac{1}{W}$

From the above set of inequalities,

C = $1.0\mu F$
R_s = 20ohms
R_l = 10kohms

6.5.3 *Data Communications*

listed in appendix E.1 is the computer program for Data Communications.

6.5.4 *Control Transmission*

Digital communications code data in a way completely different from analog communications. Amplitude-Shift Keying (ASK) produces data by a sine wave which turns on and off for high and low values. Phase-Shift Keying (PSK) involves a 90 deg phase shift for low values. Finally, Frequency-Shift Keying has two frequencies which identify either a high or low value.

In sending these signals, a parity is usually sent to insure proper data has been received. The parity bit usually transmits a high value for an odd number of high values in the data. Aside from this, a special combination of bits characterize the start of a data segment.

Digital signals lend themselves to data transmission since the information usually has already been coded in binary form. In transmitting the signal to noise ratio plays a smaller role in receiving correct data. Digital communications transmits no sidebands, therefore

$S_{sys} = \frac{1}{2}A_c^2 = 24.5\text{W}$

6.6 Summary

This is by no means a thorough treatment of the Lunar ARTS navigation system, but it outlines the major ideas and components. Most of the basic technology is developed and has been used or is in use today in NASA vehicles like Skylab or the Space Shuttle. Advances in technology are most felt in the area of computing power, in the way of gigabyte memory and super fast algorithms. The use of the HUD is a major concept that can be applied to any EVA. Two major considerations for the operation of electronic equipment in an open space (virtually) environment are radiation effects and temperature variations. Electronic components must be sufficiently radiation hardened and be able to withstand extreme temperature variations and gradients. All systems and components incorporate maximum modularity to facilitate regular and emergency repair and maintenance. They are detachable in a way that takes into account the problem of lunar dust infiltration. This problem with dust also mandates very tight sealing of component cases.

Each information type sent by the communication system requires a different design for the scheme used in the transmission of signals. The voice signals, for noise considerations, optimize transmission with FM transmission. The video signals, unlike the voice signals, contain frequencies in the low Hertz range and therefore lend to VSB modulation which save frequencies on the edge of the bandwidth. The data signals require a multiplexer because of the numerous and varied signals. Finally, the control signals can easily use byte size data to characterize 254 separate control conditions, making use of reliable digital transmission.

7. Heat Rejection and Protection

7.1 Introduction

The lunar ARTS vehicle has to be equipped with a means of protecting the vehicle from the environment it will encounter on the moon and a means of rejecting heat from the power system and the electrical equipment. The heat rejection system for the power system will incorporate a continuous loop of water originating in the water storage tank to reject the heat from the fuel cell stack. The water will pass from the water tank, through the stacks (to take away the by-products of water and heat), to a heat rejection system or storage system, and back to the water tank to be used again. The vehicle will be protected from meteoroid impact, solar flares, and dust accumulation. The protection and heat rejection systems depend greatly upon each other and were designed accordingly.

7.2 Constraints

Worst case scenario is taken into account for all calculations. This will occur when the sun is directly over the vehicle causing a lunar surface temperature of 230 °F or 383°K to be experienced. During a lunar night, the temperature of the surface is at 4°K.

7.3 Heat Rejection

7.3.1 Description

Both the fuel cell system which powers the lunar rover and the electronic equipment give off heat which has to be rejected. Several different means of rejecting the heat were studied and the system which optimized the weight, amount of space, and amount of heat rejected was chosen. The system chosen to reject heat from the power system uses both active and passive cooling. This system uses a combination of a radiator and storage system during the lunar days and only a radiator during the lunar nights. Multi-layer insulation blankets will be used on those components which are required to be kept at a constant temperature.

7.3.2 Additional Constraints

The heat rejection system is dependent upon the environment on the moon. The incident radiant flux from the sun is 1360 W/m^2. The surrounding temperature is assumed to be that of deep space or -269°C (4°K). The heat rejection system must be capable of delivering 400 W of heat from the fuel cell stacks. The temperature of the water entering the heat rejection system will be at 96°C or 369°K while the temperature leaving the system is required to be 85°C or 358°K. The amount of heat which has to be removed from the electrical components is 43.2 W. The systems chosen also have to provide for both meteoroid and dust protection. It is assumed that the temperature at the lunar base will be kept at 22°C or 295°K.

7.3.3 Equivalent Heat Sink Temperature

Before deciding what type of heat rejection system is necessary to carry away the waste heat from the fuel cell stack, the equivalent heat sink temperature must be calculated. It is desired that the equivalent sink temperature be as low as possible to gain maximum efficiency from the heat rejection system. A larger temperature differential between the heat rejection system and the surrounding temperatures will give a greater heat rejection capability provided the heat rejection system is at a higher temperature than the equivalent heat sink temperature.

The equivalent heat sink temperature is the temperature at which the waste heat rejection system (radiator or storage system) would experience as a result from the surrounding temperatures. During the lunar day contributing factors include the lunar surface, solar flux, deep space, and the chassis of the vehicle. During the lunar night the equivalent sink temperature will be that of deep space or -269°C (4°K) because there is no solar flux to contribute a temperature variation to the vehicle or the lunar surface. The following paragraphs describe the procedure in calculating the equivalent sink temperature during a lunar day.

The sun delivers a flux of 1360 W/m^2 which is a major contributor to the equivalent sink temperature. In order to decrease the temperature contribution to the heat rejection system by the sun's incident flux, a solar shield with an assumed top surface emissivity of .9 and an reflectivity of .9 was placed on top of the vehicle to block the sun's irradiation. Using a heat balance equation, Calculations in appendix F.1 show that the sun's irradiation would cause the solar shield to be a temperature of -46°C (227°K). This is the surrounding temperature above the radiator.

The lunar surface has the radiation characteristic of an emissivity of 1.0 (perfect blackbody) and an absorptivity of .9. Calculations in appendix F.1 show the temperature of the moon to be at 110°C (383°K). Without thermal protection on the sides of the vehicle (the chassis are designed such that the sides of the vehicle are open to the environment) the surface of the moon would emit a large heat flux to the heat rejection system. In order to decrease this amount of flux towards the heat rejection system, light weight covers are placed on the open sides of the chassis to block the flux contribution of the lunar surface. Calculation in appendix F.1 show that placing lightweight shields on the sides of the vehicle with an outside (the side facing the lunar surface) emissivity of .06 and an absorptivity of .12, the temperature of the sides of the vehicle is 97°C (370°K).

The bottom of the vehicle will contribute the same amount of heat flux to the equivalent sink temperature as the sides of the vehicle. Even though the solar flux will be blocked by the top of the vehicle, the vehicle will spend most of its time moving and thus it will see the same flux from the surface of the moon since the lunar surface areas that it passes over will have been at a high temperature and will not have time to see the effect of the blocked solar radiation. The fuel cell system and the plumbing will be enclosed entirely in a multi-layer insulation blanket in order to block out the temperature effects that the bottom of the vehicle will contribute to the equivalent sink temperature of the vehicle. The bottom temperature of the vehicle will be the same as the equivalent heat sink temperature as it will make no contributions to the equivalent heat sink temperature of the vehicle.

The heat rejection system is to reject (or store in the cases that the surrounding temperatures are too high) 400 W of heat from the fuel cell stack. Figure 7.1 shows the heat contribution by the solar flux as well as the surrounding temperatures which contribute to the equivalent sink temperature of the vehicle. Since the areas of each of the surfaces are different, the equivalent heat sink temperature was calculated by using a heat balance equation with the total heat exchange between all of the surfaces to be 0 and the emissivities inside the vehicle of all the surface to be .06. Different angles of the sun will not affect the heat exchange because the shield will cover the entire cart. Each temperature term ($\epsilon\sigma[T^4_{surface} - T^4_{sink}]$) was multiplied by the ratio of its area over the total area to account for the different areas in their contribution to the total sink temperature (i.e. the solar shield on top of the vehicle is at a colder temperature but has more area than one of the sides of the vehicle at a higher temperature). Calculations in appendix F.1 show that the equivalent sink temperature inside the vehicle during the lunar day was 70°C or 343°K.

At this temperature which is below the existing temperature of the fluid leaving the stacks, it is possible to radiate heat that is generated by the power system. The next subsections describe the material choices that match the properties as described above.

7.3.3.1 Material Choice-Solar Shield

The solar shield must have an emissivity of .9 and a reflectivity of .9 on the top surface of the solar shield. It is proposed to place a thin layer of aluminum which is coated with YB-71 zinc orthotitanate silicate coating (paint). The aluminum will serve as a lightweight solar shield that will not bend under its own weight, and will also serve as a meteoroid protection shield for the contents inside the vehicle. The shield will be placed on top of the vehicle with velcro. This will enable the shield to keep its place without the use of extra support which would add extra weight and obstruction on the vehicle. The YB-71 paint will withstand lunar conditions because it is an inorganic coating which is stable in a UV vacuum environment and has very little change in

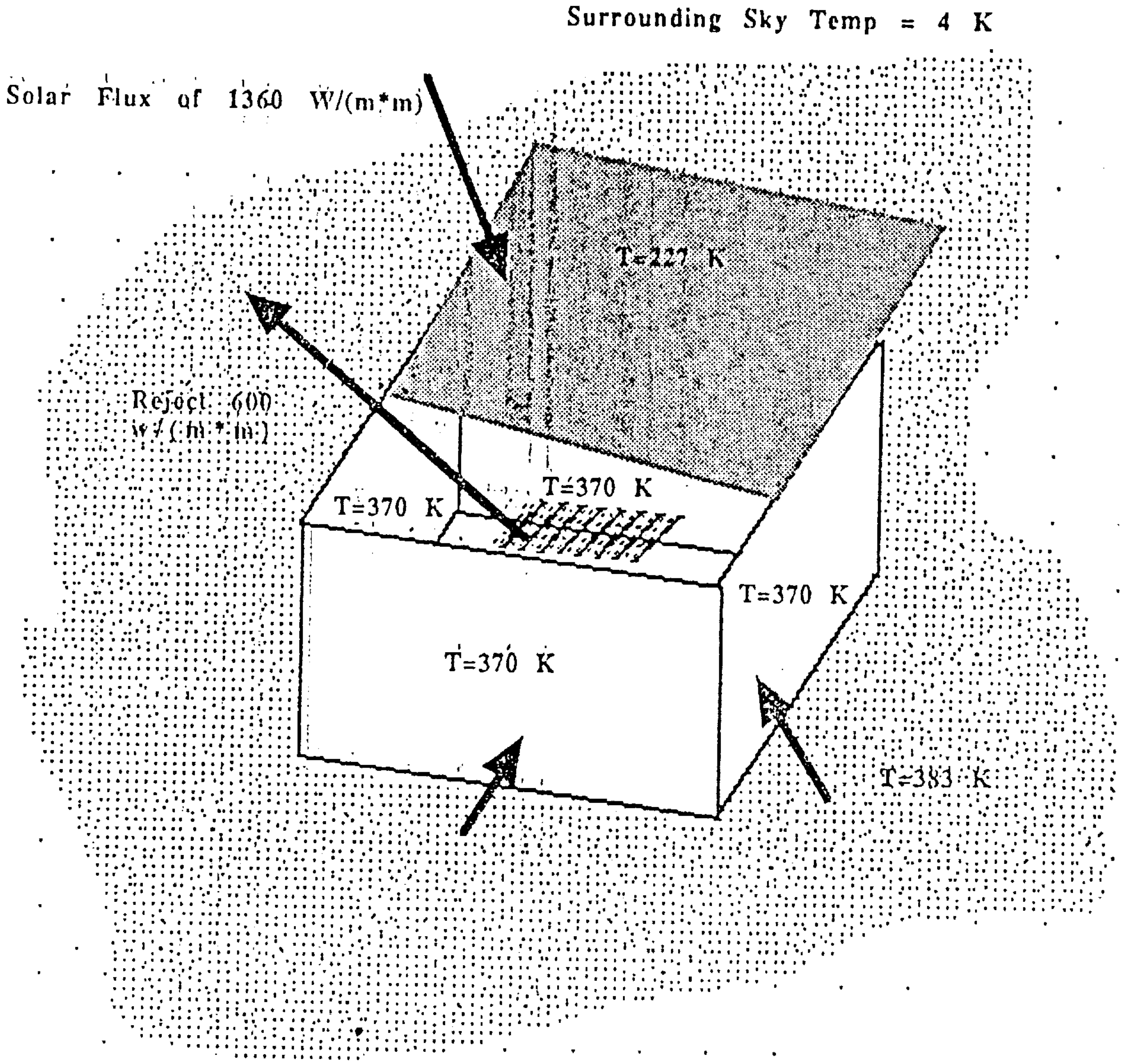

Figure 7.1. Heat fluxes and surrounding temperature contributions to the Lunar ARTS heat rejection system.

the α_s/ϵ over long periods of time [22] . Since the bottom of the solar shield is to contribute as little flux to the heat rejection system as possible, the underside of the solar shield (the side facing the vehicle) will have a coating of black nickel oxide which has an emissivity of .08 and an absorptivity of .92. A low emissivity will cause a small radiation flux by the shield to the heat rejection system. Calculation in appendix F.1 show the mass of the solar shield to be .0680 kg.

7.3.3.2 *Material Choice-Side Panels*

The only purpose of the side panel is to prevent the radiation flux coming from the lunar surface as a result of the moon's high emissivity. A sheet of single goldized Kapton will be used on each vertical side of the vehicle. The Kapton will be goldized on the side that faces the lunar surface. Kapton strands keeps 75 percent of their tensile strength while mylar deteriorates at a temperature above 140°C (-133°K). The goldized film also has a high stability in a vacuum with a low emissivity [23] . The emissivity of the goldized Kapton is .06 while having a reflectivity of .88. The weight penalty added to the vehicle will be negligible.

7.3.3.3 *Material Choice-Multi-layer Insulation Blanket*

The multi-layer insulation will be placed on the bottom of the vehicle. It will consist of several layers of radiation reflector shields of low emittance which minimize heat exchange with the surroundings. Goldized Kapton will be used for the layers in the blanket for the same reasons explained in the above section. Figure 7.2 shows the composition of the multi-layer insulation blanket.

The top cover consists of teflon coated fiberglass "beta cloth" (3 mm) to provide both handling and meteoroid protection for the blanket. This material provides the required protection and at the acceptable degradable value of .36 (NASA standards for a protection blanket cover allows a degradation of 36% of the material) [23]It has a transmissivity of .26 which would let heat into the blanket where it would become trapped and would cause the second layer of material in the blanket to be higher than the outside temperature. A second layer of single goldized Kapton would serve as a "light block" for the transmitted light and reduce the amount of heat entering the blanket. It is only goldized on the side facing the outer cover so as not to transfer heat downward into the blanket. In order to avoid direct contact between reflectors which could produce a conductive heat short, layers of dacron net separate each layer of double goldized material. The bottom (inner) layer of material is a double goldized Kapton nomex net reinforced material. The nomex material gives strength to the blanket and provides protection on the inner side of the blanket.

Lab tests [23] have shown that the optimum number of layers for the blanket are 19 reflector layers of double goldized Kapton separated by 20 layers of dacron net. The total thickness of the blanket is 1 cm.

7.3.4 *Heat Rejection from Power Systems*

In designing a heat rejection system for the power system, the first option was to use a radiator to reject the heat. Since the water coming into the system is at 96°C (369°K) and the heat sink temperature with the cover blocking the radiant solar flux is at 70°C (343°K), it would be impossible to radiate all the heat that was produced by the power system since the temperature differentials between the equivalent heat sink temperature and the radiator temperature (96°) (369°K) was not large enough.

The second option was to store the 4 kWhr and then reject the heat at the lunar base by allowing it to radiate in a room which is maintained at 22°C (295°K). The heat would be stored using potassium latent heat storage. In latent heat storage, energy is used to change the phase of the material. Energy is stored in the material as the temperature of the material increases to the melting point while the temperature of the fluid transporting the hot liquid decreases. Energy is then used to change the phase of the material. Finally more energy is stored in the material in the liquid state. The hot water coming from the stack will be pumped through the storage system such that the hot liquid will provide energy to the storage system. The heat will be transferred to the potassium through conduction. The water will not be contaminated by the potassium since the two materials will never come in contact. Using latent heat storage with potassium as the material,

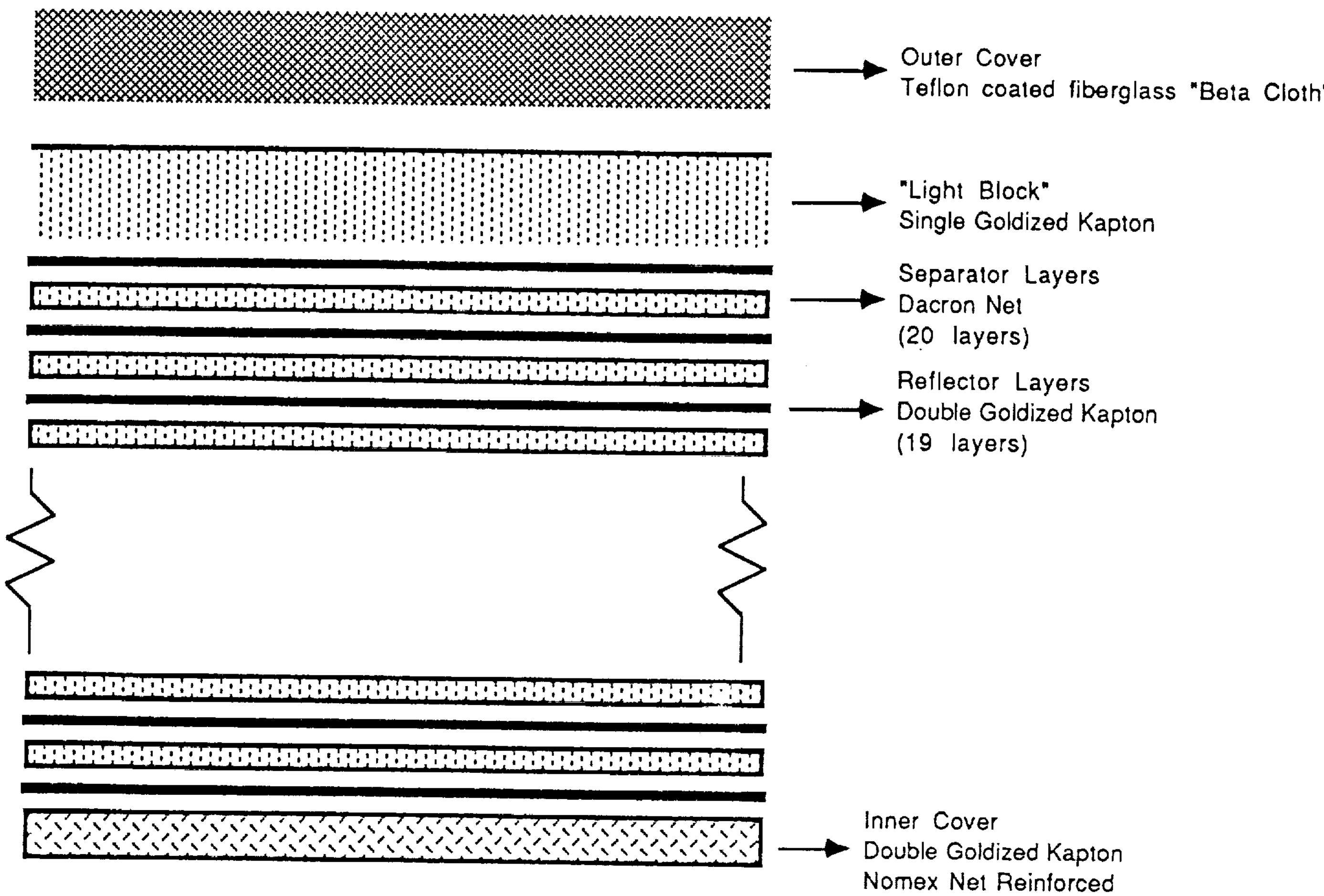

Figure 7.2. Multi-layer insulation blanket.

it would require 126 kg of potassium and a volume of .17 m^3 as shown in appendix F.1. The potassium will be enclosed in a 1 inch thick Nickel 200 box. Nickel is compatible with potassium[24]. Nickel is appropriate in the temperature range (21°C (294°K) to 96°C (360°K)) of the storage system [25]. Sodium was also considered as the storage material but the water leaving the stacks is at 96°C (369°K) and the melting point of sodium is 97.83°C (370.83°K)[25]. Therefore, the sodium would not be used to its full potential since it would never melt. Storing all of the energy was eliminated because of weight and also because it would be possible to reject all of the heat at night.

During the lunar night, it would be more efficient to reject the 400 W of heat to the environment since the heat sink temperature during a lunar night is -269°C (4°K). It is inefficient and more costly to manufacture and send two different systems to the moon; therefore, a combination of radiation rejection and latent heat storage will be used as the heat rejection system. This system has the capabilities of being operational both during lunar days and lunar nights. A top view of the heat rejection system during a lunar night is shown in Figure 7.3 . The radiator will be optimized for rejecting the 400 W of heat at night, as it will be the only means of rejecting the heat. A pipe will be used to close the second loop. Water will constantly flow through this loop at night so that the water will not freeze. During a lunar day, the same radiator will be used along with a storage system to reject the heat. The pipe will be removed and the storage system set in place. During the lunar day, the storage system will store the heat that the radiator cannot radiate. The radiator will reject 113.4 W of heat and the storage system will store the remaining 296 W. This storage system will require 92.7 kg of potassium and a volume of .12 m^3. After the mission, the storage system will be removed using quick connect valves and will be placed at the base to cool from 96°c (369°K) to 23°C (296°K). It will take 19 hours to cool as shown in appendix F.1. Three storage systems will be available at the base in the event that the astronauts wish to go back out. A top view of the heat rejection system along with the power system during the day is shown in Figure 7.4 . A side view of the power cart during the day is shown in Figure 7.5 . All components are placed in the cart in order to obtain a desirable center of gravity.

7.3.4.1 *Radiator Design*

The radiator is a tube-fin radiator. The radiator will be made of titanium because of its high strength, high impact resistance, and low density [25]. Titanium is also compatible with water which is a requirement since the water is in contact with the titanium [24]. The water coming from the stack will be used as the working fluid in the radiator. Water is appropriate since the fluid will enter the radiator at 96°C (369°k) and will leave at 85°C (358°K) and will be kept at 15 psi. The radiator will be 4.08 ft (1.24 m) wide by 3 ft (.9144 m) long. It will consist of 6 tubes each having a thickness of .15 in (.0038 m). This thickness includes the armor thickness which will protect the tubes from meteoroid damage. All 6 tubes can be used to reject heat but only four tubes were used to design the radiator in the event that a meteoroid would damage a tube. In the event that a meteoroid does puncture a tube, a check valve at the end of the tube will detect a pressure drop and will shut off the electrically controlled ball valve at the entrance of the tube. The fins will be 3.75 in (.095 m) long and .15 in (.0038 m) thick. See appendix F.1 for radiator calculations. A picture of the radiator is shown in Figure 7.6 .The radiator will be coated on the top with white zinc oxide paint which will increase the emissivity to .93 and decrease the absorptivity to .16. It is desirable to have a high emissivity and a low absorptivity so that the radiator will give off heat but will not absorb heat. The bottom of the radiator will be coated with a thin layer of anodized aluminum coating which has an emissivity of .03 and an absorptivity of .09 [18]. It is desirable to have a low emissivity and a low absorptivity on the bottom of the radiator so that the heat will not be rejected to the bottom of the cart and heat will not be absorbed by the radiator from the bottom of the cart. At night the radiator will reject 491 W of heat through 4 tubes with an emissivity of .9. The radiator will be able to reject 400 W as long as the emissivity remains above .75. During the day, the radiator will reject 113.4 W and 296 W of heat will be stored. The water will be pumped through the radiator at a mass flow rate of .011 kg/s (split up between 4 tubes). The valves will be electrically controlled so that the storage system will not be used unless the radiator can not handle the load. Calculations were done to make sure the radiator would not bend because of its own weight. These calculations are shown in appendix F.1

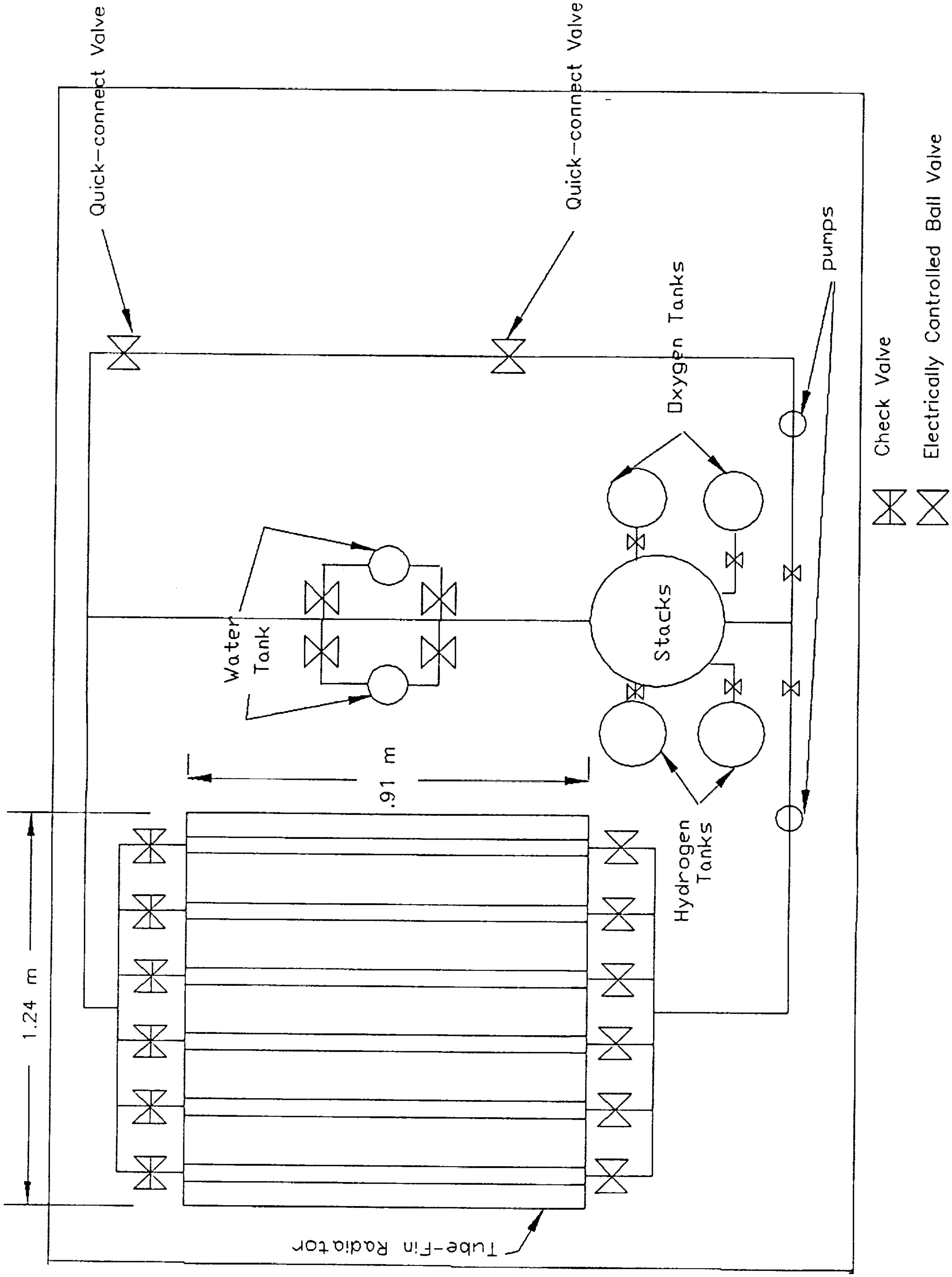

Figure 7.3. Top view of power cart at night.

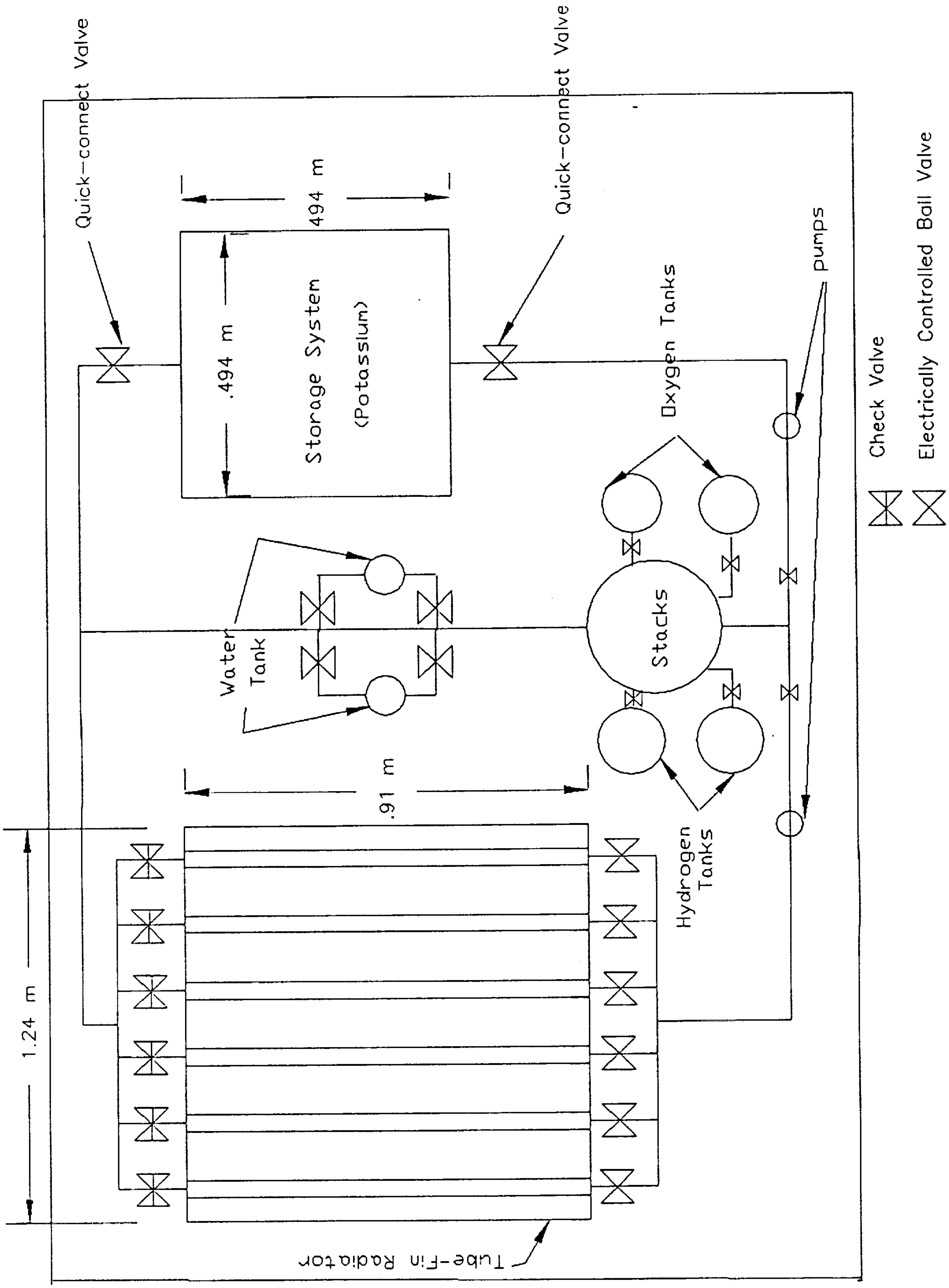

Figure 7.4. Top view of power cart during day.

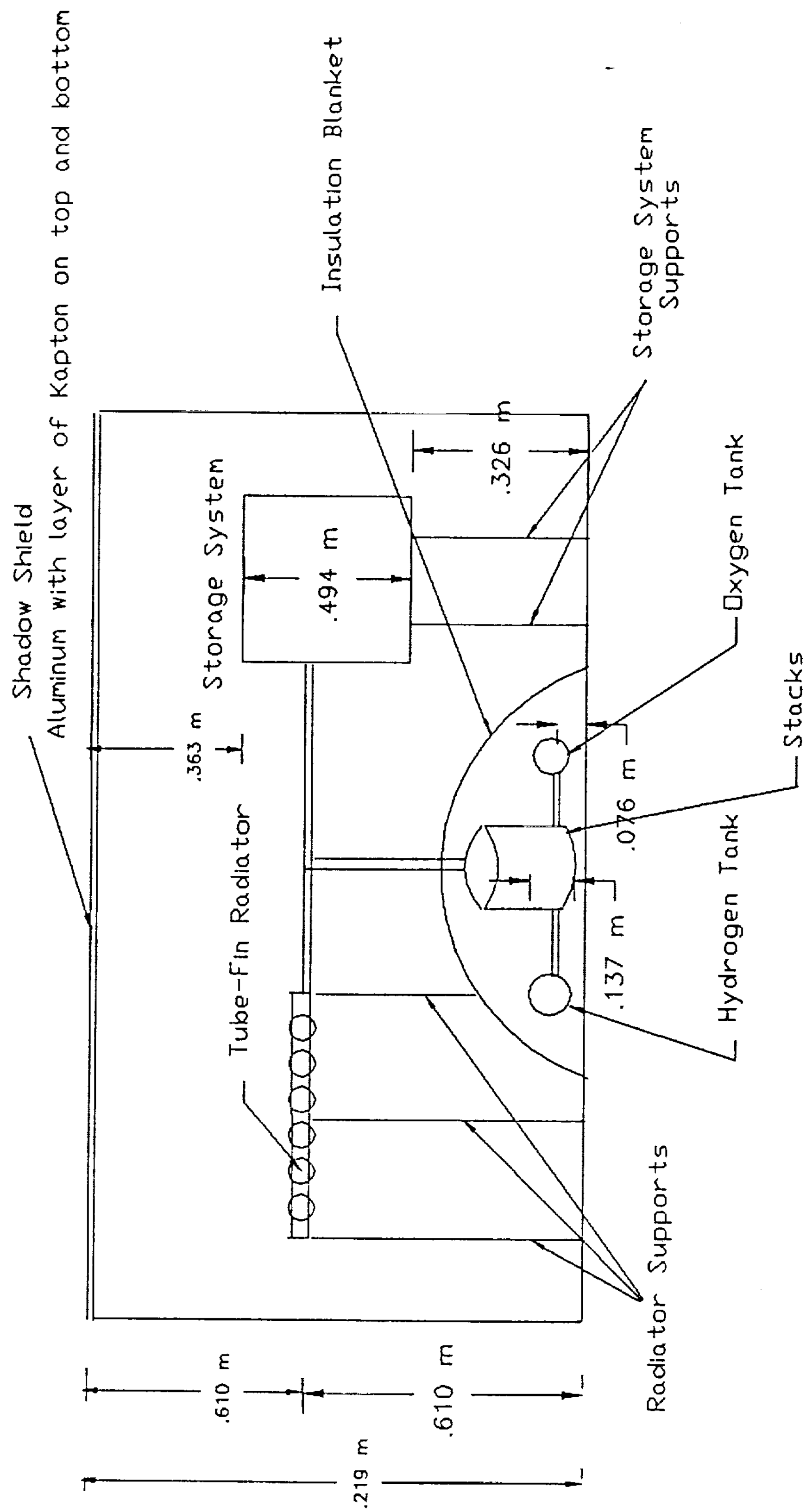

Figure 7.5. Side view of power cart during day.

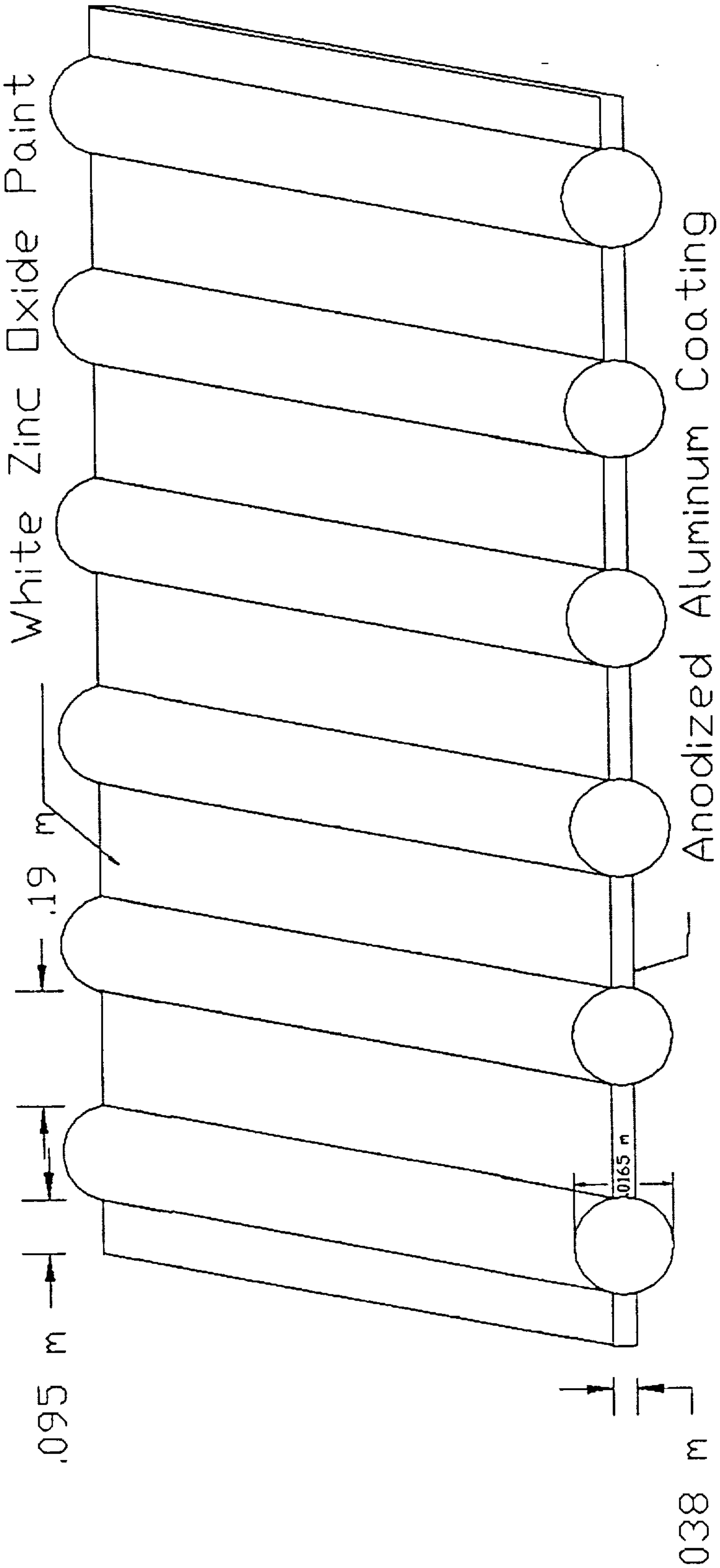

Figure 7.6. Tube-fin radiator.

The heat rejection system fits inside of the cart and has a mass of 126.2 kg which includes the radiator, storage system, and the plumbing.

7.3.5 Heat Rejection from Electrical Equipment

The amount of heat that needs to be rejected from the electrical equipment is 43.28 W. The reason the heat rejection system from the second cart is not used to reject the heat from the electrical equipment is because it would be heavier and more costly to provide piping from the first cart to the second cart. The means of rejecting this heat will be a Solar Optical Radiator. A Solar Optical Radiator is made up of 1 in squares of 8 mil fused silica glass with vacuum vapor-deposited silver and inconel. Each square is mounted to an aluminum conductor plate which is used to dissipate the heat from the equipment to the radiator. Each square is placed .005 in apart to provide for thermal expansion. The radiator will be coated with a solar optical radiator (SOR) coating [4]As a second source of thermal protection, the electrical equipment will be placed behind the astronauts in a .06 in fiberglass box having .25 in aluminized mylar (15 layers) insulation with a thin layer of Aluminum 2219 Titanium alloy. The fiberglass box is necessary in order to keep the equipment from radiating to each other and to provide dust and meteoroid protection. The box will have a removable cover. The cover will be used during the lunar day when the heat sink temperature is too high to radiate. The heat will be absorbed by the box and the equipment will also serve as its own heat sink. The cover will be removed at night when the heat sink temperature is very low.

7.3.6 Summary

The water that leaves the power system at 96°C (369°K) carries 400 W of heat which has to be rejected. The heat sink temperature to which the radiator radiates is dependent on the radiator's surroundings. During a lunar day when the heat sink temperature is 70°C (343°K) with a cover over the cart and the heat will be rejected by using a titanium tube-fin radiator and a potassium latent heat storage system. During a lunar night when the heat sink temperature is -269°C (4°K), the titanium tube-fin radiator will be adequate to radiate the 400 W. Thermally insulated blankets are used to keep the power system and plumbing at a constant temperature. The power cart is lined with goldized Kapton to prevent radiation flux from the environment. The entire heat rejection system provides for both meteoroid and dust protection.

The electrical equipment has to reject 43.2 W of heat. Solar Optical Radiators placed on an aluminized conductor plate are used to radiate the heat. The electrical equipment is also placed within a fiberglass box to protect against the equipment from radiating to each other and also to serve as meteoroid and dust protection.

7.4 Solar Flare Protection

7.4.1 Description

A main concern during the vehicle's traverses on the lunar surface will be the radiation effects on both the astronauts and vehicle. Radiation effects occur in two forms: initial radiation dosage and secondary particle build-up.

7.4.2 Additionl Constraints

In calculating the radiation effects on the vehicle a worst case scenario is assumed (i.e., worst case solar flare, worst case galactic particle radiation). The radiation protection design will be to minimize transportation vehicle weight penalties due to shielding while providing maximum possible protection from radiation. Since major solar flares can last between a few hours to a few days, partial protection for the astronauts will be provided. Full protection is provided upon immediate return to the base.

7.4.3 *Radiation Protection*

The average radiation dosage allowed for an astronaut during his lifetime career is 200 Roentgen Equivalent Man (REMs) [26] . This dosage must be spread out over a period of years; if there is too much radiation exposure in too little time, it can result in sickness and possibly death [27] .

There are three types of radiation that the astronauts and the Lunar ARTS vehicle will experience while on the lunar surface: galactic cosmic radiation, solar proton events, and solar flares. galactic cosmic radiation consists of very energetic protons originating from space. These cosmic rays deliver from 20 to 50 REMs a year. This radiation exposure is at its highest level during the solar minimum (when the solar radiation exposure is at its lowest level). The largest danger imposed by this type of radiation is the secondary particles which build-up within exposed material. Solar radiation consists of two components, solar proton events and solar flares. Both types of radiation follow a field line pattern when emitting radiation (high accelerated protons). It is this reason why solar proton events can be predicted. They are the most common type of radiation emitted by the sun and follow an 11 year cycle. Even though solar flares follow field line patterns similar to that of the solar proton events, solar flare occurrences are very unpredictable. Scientists can determine a time period in which flares are most likely to appear by counting the number of sun spots visible on the sun's surface. They have been unsuccessful when trying to predict a flare occurrence (spanning between 3 and 24 hours). [26] A solar flare is the most dangerous radiation event that the astronaut will encounter because it delivers as much as 17 REMs per hour when unshielded (This occurrence happened in August 1972 [28]). A dosage of 220 REM in one day will result in death.

For galactic cosmic radiation and solar proton events, NASA has incorporated a surface density of .5 g/cm of aluminum shielding in the Extravehicular Mobility Units (EMU - these are the suits the astronauts wear upon conducting Extra Vehicular Activities (EVA)). It would take the astronauts approximately 8 years to reach the 200 REM radiation dosage limit; this consists of 6 90 day excursions of 8 hours per day.

It is assumed that during probable times for occurrences of solar flares, the Lunar ARTS vehicle will be no more than a four hour return from base. The shielding provided for the astronauts must keep the radiation dosage received at a maximum of 15 REMs. This is a combination of 5 REMs allowed for regular EVA excursions and an emergency dosage of 10 REMs in the case of a solar flare. If 15 REMs maximum are allowed for four hours then the shielding must not allow the astronaut to receive more than 3.75 REMs per hour. Vehicle traverses will be kept to a minimum during the cycles where solar flares are most probable. We suggest NASA follow the same guidelines for operating the Lunar ARTS as those set for the Lunar Roving Vehicle on the Apollo 15 mission. [29].

In the case when a solar flare is predicted, the astronauts will have a partial protection garment (located on the second cart of the Lunar ARTS) to protect themselves from radiation. Radiation levels will reach a peak in 3-8 hours from the time they are first detected. The partial shielding garment should be worn when a solar flare emergency has been declared. Detection can either be done by monitoring the dosimeters carried by the astronauts or by continuous communication with the base. This garment is a flexible "blanket " garment. It will cover the astronaut from head to knee with slits for the arms and an opening for the astronauts eyes (Figure 7.7) . Candidates for this material are aluminum, water and carbon fiber cloth. Water was rejected because it would be difficult to continually encase water around the astronaut. Aluminum has proven to be successful in many space applications, but calculations in A*.* show a mass of 615 kg for the garment (a surface density of 10 g/cm^2 is required for adequate radiation protection). Carbon fiber cloth provides the same protection as the aluminum but at a smaller mass penalty. Calculations in appendix F.2 show the mass of the carbon fiber cloth needed to shield the astronauts to be 4.0 kg (8 centimeters of carbon fiber cloth is equal in protection against radiation as 10 centimeters of aluminum). This will be adequate protection for the astronauts until they can return to the base (4 hours max). Carbon fiber cloth is the choice of radiation protection blanket material.

The second area of concern is secondary particle build-up on the vehicle. The worst case scenario would be the cargo cart or the cart with the most amount of aluminum material. galactic cosmic radiation is the major cause of the radiation build-up due to heavy protons that imbed themselves into material. Worst case scenario for the galactic cosmic radiation is during the solar minimum period of time. Calculations in appendix

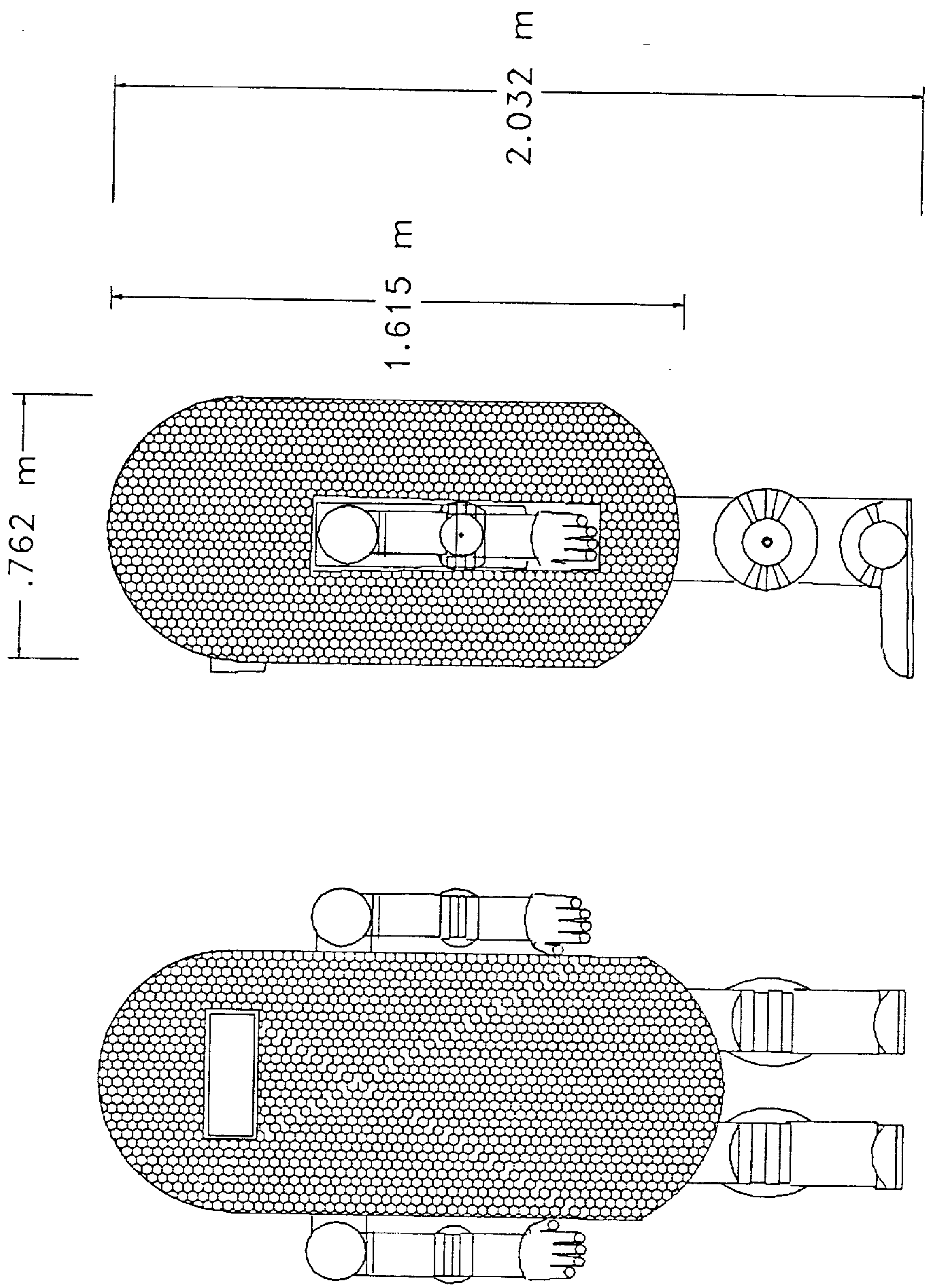

Figure 7.7. Solar flare protection garment.

F.2 show the surface density of the vehicle (which comprises of 2014 aluminum at a thickness of 1/8 inch (.3175 cm) to be .1171 g/cm^2. A peak radiation dosage of 4.67 REMs per year will occur for an aluminum density of 0.1 g/cm^2. This is the amount of radiation that will be contained in the material after 1 year's time. Over a ten year period, there will be a maximum of 46.7 REMs in the material of the Lunar ARTS. The vehicle will be coated to avoid oxidation of the aluminum (which would raise the emissivity of the material). The emissivity of aluminum peaks at a maximum of .11 for a temperature of 200 degrees celsius [25].

7.5 Meteoroid Protection

7.5.1 *Description*

A major problem that the lunar roving vehicle will encounter is the threat of meteoroid impact. Previous lunar roving vehicles have found the threat of meteoroid impact to be a reality. Meteoroids can be classified by a mass, density, and velocity. There are several critical components on the vehicle which should be protected from meteoroid impact. These areas include the chassis, radiator, reactant tanks, electronic equipment, and the astronauts.

7.5.2 *Additional Constraints*

In protecting the critical components from meteoroid threat, several assumptions have to made. The vehicle was designed to be protected from a meteoroid having a mass of 1.5×10^-5 g, a density of .5 g/cm^3, and traveling at a velocity of 20 km/s. These are the characteristics of the meteoroid that the protection was designed for but does not necessarily represent the worst meteoroid impact.

7.5.3 *Protection*

The power system on the cart uses liquid hydrogen and liquid oxygen as reactants for the PEM fuel cell system. The reactants are stored as cryogenic liquids. The tank design is explained in chapter 3; section 3.4.3. The design uses an inner pressure vessel (Aluminum 2219) and an outer pressure vessel (Aluminum 6061) with 90 layers of multilayer insulation [9]The outer pressure vessel along with the multilayer insulation is efficient in protecting the reactant tanks from meteoroid impact.

The means of rejecting heat from the fuel cells to the environment will be through a titanium tube-fin radiator and a storage system. The radiator will be made of titanium because of its low density, good impact resistance, ease of fabrication, and high strength [30]. The radiator has to be protected from meteoroid impact. If a meteoroid were to penetrate a tube of the radiator, the water would escape and would leave the tube useless and would thus decrease the amount of heat that can be radiated. The tube would be shut off using valves when a pressure difference is detected. If the meteoroid does not penetrate the tube, it will not affect the operation of it. The radiator was designed for 50% survival probability. In order to accomplish this, each tube is individually armored by adding a certain thickness of titanium to prevent penetration by a meteoroid with a specific mass. The threshold penetration thickness which will provide protection against the meteoroid impact is 1.18 mm for each tube. The armor thickness is designed for a specific mass of 1.5 x 10^-5 g traveling at 20 km/s. Therefore, any meteoroid over this mass might cause penetration and redundancy will have to be incorporated into the design when determining the number of tubes needed [31].

The chassis of the lunar roving vehicle will be made of Aluminum 2219. No extra meteoroid protection will be necessary since the most damage that the meteoroid will induce is dents.

The electronic equipment which is located behind the astronauts's seats in the lunar roving vehicle will have both thermal and meteoroid protection which will be incorporated together. In order to keep thermal control of the equipment, it will be placed in a .06 in fiberglass box having .25 in aluminized mylar (15 layers) insulation with a thin layer of Aluminum 2219 Titanium alloy. It will have a cover made of the same materials. The equipment will be protected from meteoroid impact by the thin layer of Aluminum 2219 Titanium alloy. Aluminum 2219 has a density of .101 lb/in^3 and a tensile strength of 25 psi [25].

The men will be protected from meteoroid impact by their EVA suits.

7.5.4 Summary

Protection against meteoroid impact is important for both the lives of the astronauts and the life of the lunar roving vehicle. The areas which are protected from meteoroid impact are the radiator, reactant tanks, electronic equipment, chassis, and men. Calculations for meteoroid protection can be found in appendix F.3.

7.6 Dust Protection

7.6.1 Description

The dust on the lunar surface adds many problems in the design of the lunar ARTS. The rate and degree of dust accumulation is unknown during lunar operation. It can accumulate on face plates and can obscure the vision of the astronauts. The dust can accumulate on the radiator which will lower the emissivity and raise the absorptivity of the radiator's surface. The lunar surface can contain rocks and pebbles which can be hurled up at the astronauts. The lunar dust can also accumulate on the electrical equipment and instead of allowing it to reject the heat it will absorb it. These are all problems which the lunar dust will cause.

7.6.2 Additional Constraints

There have been studies done on the dust problem on the moon[32]. The dust adheres easily but is difficult to remove. Some removal techniques include brushes, electrostatic charge control device, or a self cleansing surface[33]. It is assumed that the vehicle will be cleaned free of dust when it returns to the base. The radiators, fenders, flaps, electrical equipment, and the chassis will be cleaned. Brushes will be provided on the vehicle to remove the accumulated dust from the astronaut's helmet since the astronauts will need clear vision to complete the mission. Bellows will be placed over the hitch to protect the hitch from dust accumulation.

7.6.3 Prevention of Dust Accumulation

One way to prevent the dust from accumulating on the vehicle is to prevent the dust floating in the environment. One of the main causes of this is the dust being agitated from the tires. One way to prevent this is to cover the wheels with a fender and flaps. Another option that was looked into was a skirt but since the wheels are 2.3 m (7.5 ft) in diameter and the cart is only 2.75 m (9 ft) in length, there would only be approximately .229 m (.75 ft) on each end. The exact trajectory of the dust as it is being agitated by the wheels is unknown [32]but a .75 foot skirt on each side of the wheel will not keep the dust away form the cart. The wheels are hemispherical; therefore, the wheel has to be covered in its entirety. The fender is shown in Figure 7.8 . It will be placed 6 in from the wheel and will be attached to the end of the shaft with two .014 m (.55 in) diameter Aluminum 2024 T6 rod which are 1.15 m (3.77 ft) in length as shown in Figure 7.9 . The fender will also be connected to the vehicle by two bolts attached to the backplate as shown in Figure 7.10 . The fender is made of filament wound Kevlar 49/epoxy matrix. The density of filament wound Kevlar 49/epoxy matrix is 1480 kg/m^3 and has a tensile strength of 3617 MPa[34]. "Sandblasting" by the dust will not damage the fender or flaps [32]. Other materials to use for the fender and flaps were looked into such as S glass, aluminum, and fiberglass polyester composites. These materials were not lower in weight and had a lower tensile strength. The fenders are .0013 m (.05 in) thick and weigh 8.7 kg each.

The fender alone is not enough to prevent dust from flying up onto the vehicle. Flaps were also designed and are shown in Figure 7.11 . The flaps are also made of Kevlar 49 and are .61 m (2 ft) long. There is .7389 m (2.4 ft) distance from the ground. The flaps span the circumference of the hemispherical wheel. The flaps weigh 1.92 kg each. Therefore the total weight of the fender and flaps is 14.65 kg per wheel and 87.9 kg for the entire vehicle. This will protect the vehicle substantially from dust.

Another important area to protect against dust is the radiator. Since the dust has a high absorptivity and a low emissivity, it will raise the absorptivity and lower the emissivity of the radiator. Therefore, it needs to be protected. Lowering the emissivity and raising the absorptivity will decrease the amount of heat which can be

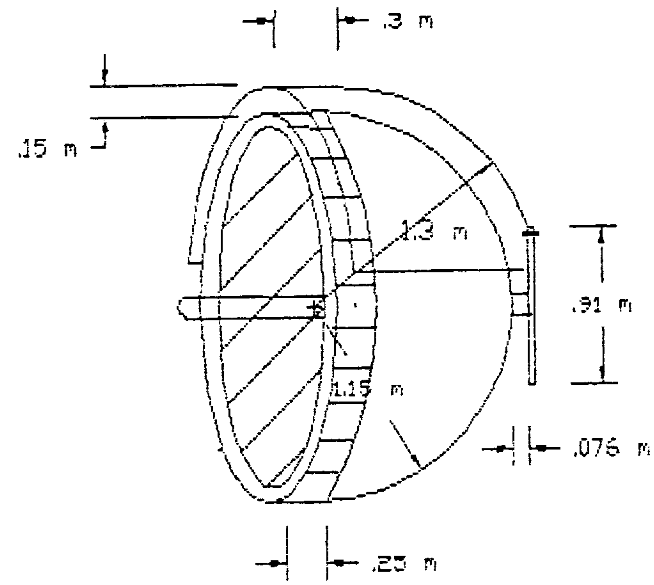

Figure 7.8. Side view of wheel and Fender.

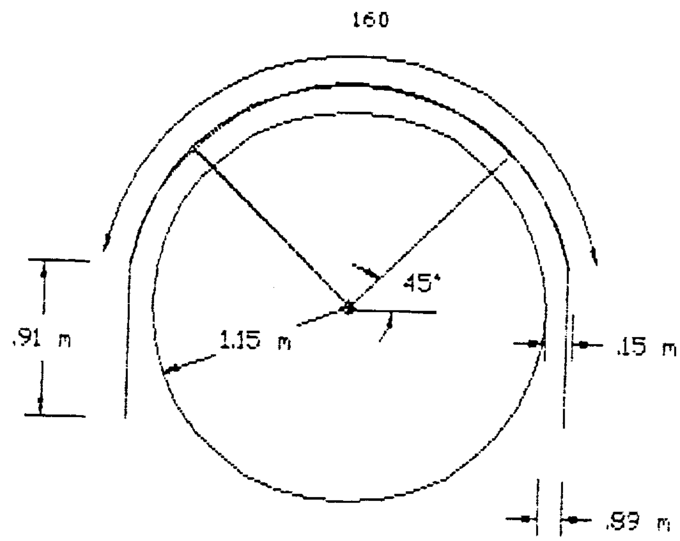

Figure 7.9. Front view of wheel, fender, and flap.

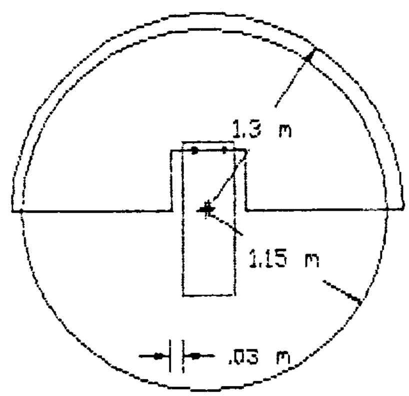

Figure 7.10. Back view of wheel and fender.

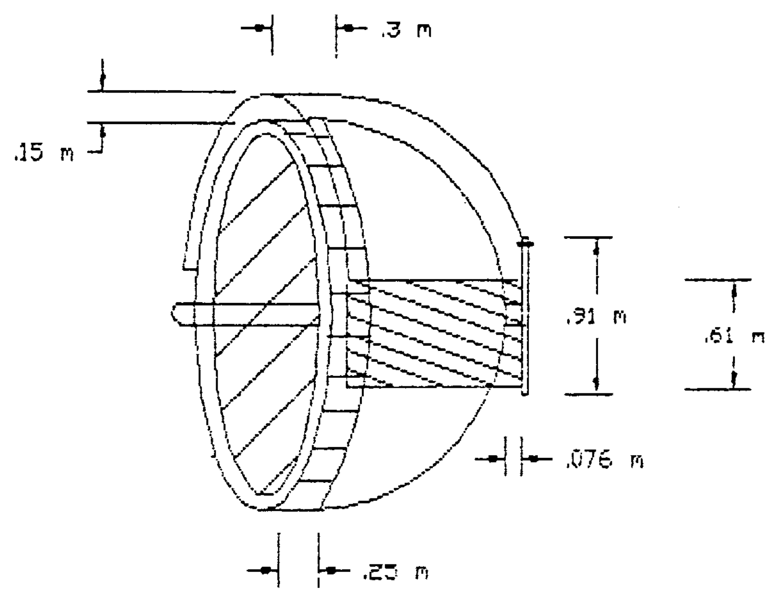

Figure 7.11. Side view of wheel, fender, and flap.

radiated. The dust protection, thermal protection, and meteoroid protection can all be taken care of together. The way to do this is to use a cover over the top of the cart. The cover will be used to prevent direct radiation from the sun and at the same time will prevent dust accumulation and meteoroid impact. The cover will be made of aluminum with a thin layer of black nickel oxide on the bottom and YB-71 zinc orthotitanate silicate coating on the top. The cover will be goldized on the top to increase the reflectivity of the cover to .9. The covers will be attached using velcro. Also, the radiator was placed inside the cart which will have less chance of dust accumulation than if it were on top of the cart.

The electrical equipment will be enclosed in a fiberglass box with a cover. This fiberglass box and cover provide thermal, meteoroid, and dust protection of the radiators. When the solar optical radiators can't radiate, the cover will be used and will protect the radiators from dust accumulation.

The power system will be protected thermally and from the dust with a thermal blanket. It is covered with Beta cloth on the inside and outside to prevent penetration of the lunar dust. It will protect the stacks, tanks, and piping and will keep the power system at a desirable and stable temperature. Calculations for the dust protection system can be found in appendix F.4.

7.6.4 Dust Removal

The problem of removing dust after it has accumulated on glass surfaces is addressed here. The primary concern is the removal of dust from electronic readout and the face masks of the EVA suits. The dust adheres to glass surfaces by electrostatic forces and contact friction. Research at NASA Houston shows that the use of copper wire brushes is the most effective method of dust removal[35]. Design of a lunar regolith remover is based on this research.

The brush design will remove the lunar dust, not just push it over. It also must be designed to be easy to hold for the astronauts, as they work out in the field. The brush is made of a one foot rod with brass bristles rotated 360° around it. 180° of the length of the brush is exposed for application while the other 180° is enclosed. On the inside of the housing, stationary scrapers run through the bristles removing excess dust in to a disposable plastic container. The brush is rotated on battery power, which can be recharged at the lunar base. The brush is shown in Figure 7.12 .

7.6.5 Summary

The vehicle will have a fender and flaps over every wheel. This will protect the vehicle from the dust blown up by the tires. The radiators will be protected from dust when they are covered but can not be protected when they are radiating heat. The power system will be covered always and thus will be protected form dust. If dust accumulates on the face plates, brushes will be available on the vehicle to remove the dust. There is no way to prevent the dust but these methods will lower the possibility of dust accumulation.

7.7 Summary

The heat rejection system and protection systems are incorporated together to provide an efficient system. The heat rejection system will consist of a tube-fin radiator in conjunction with a latent heat storage system. The electrical equipment uses solar optical radiators (SOR) to reject the heat. The radiators are protected from dust accumulation and meteoroid damage. The astronauts are protected from meteoroids with their suits but will have extra bags with will protect them from unexpected solar flares. Fenders and flaps are used over the wheels to prevent dust from being stirred up by the wheels and deposited on the vehicle. If dust does accumulate on the astronauts' face plates, brushes to remove the dust will be available on the vehicle. The power system is thermally insulated and protected from dust with a multi-layer insulated blanket. The suggestions made in this section will fully protect the vehicle and astronauts from radiation, dust, and meteoroid hazards as well as provide adequate rejection of heat from the electronic components and power systems.

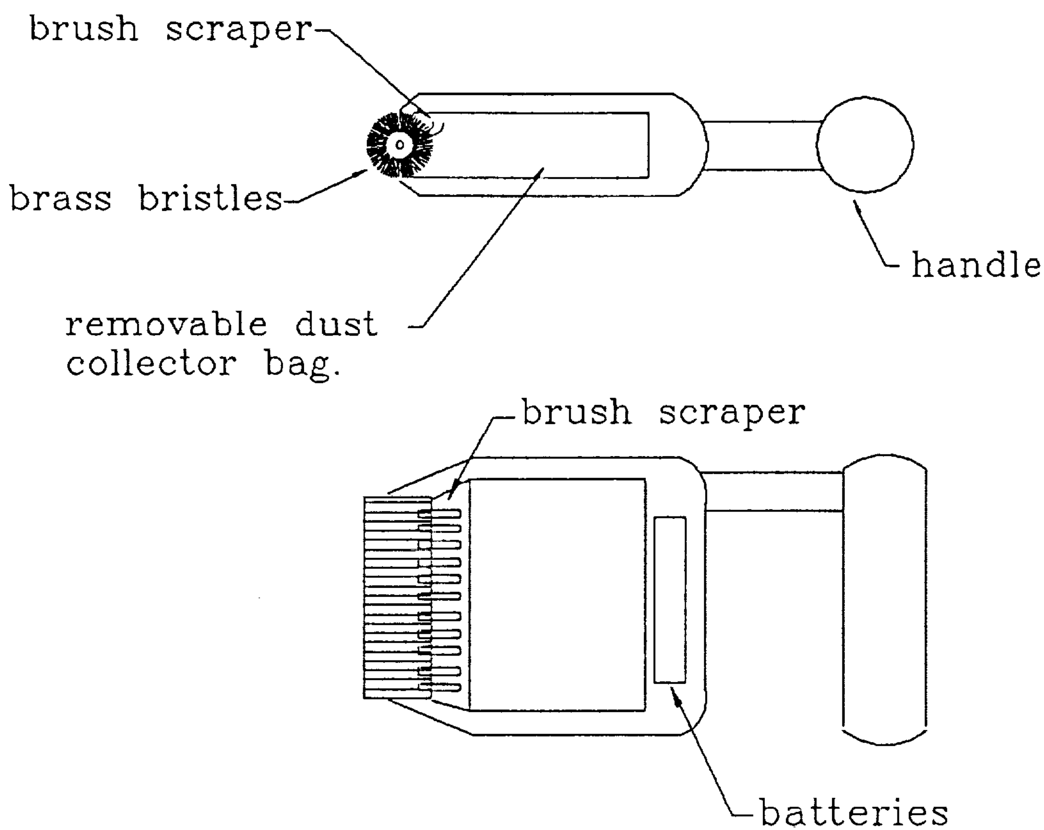

Figure 7.12. Brush for Dust Removal.

8. Prototype

8.1 Introduction

In all testing of designs some sort of prototype testing is performed, this testing usually takes several forms and levels. In the preliminary design of the LARTS system it was decided that a prototype model be built to show proof of concept for the Lunar ARTS.

8.2 Constraints

In the 1/4 scale Lunar ARTS system the preliminary proof of concept model is to demonstrate the relative motions of the vehicle suspension, wheels, and hitch assembly. This system will also show the relative electronic setup of the full scale development model, including laser range finding, radio remote control, and data uplink capability. The first generation model will not go into intensive testing as this design model is for proof of concept. A second generation model should be constructed to obtain further data.

8.3 Chassis

8.3.1 Introduction

The Lunar ARTS proposed is unique in the fact that it will articulate between each pair of wheels. Although this will increase the maneuverability of the vehicle it will also be unstable platform to operate from. Because of the instability of this design a model was constructed to study the possible problems that are related to the two-wheeled vehicle.

8.3.2 Constraints

The main parameters of the chassis for the model is that it supports the electronic and mechanical equipment and the size is 1/4 scale of the proposed lunar Lunar ARTS.

8.3.3 Chassis Design Summary

The chassis for the lunar Lunar ARTS model is based on cubic construction with added support for suspension, camera, and batteries. The size of the chassis is 1/4 scale of the proposed lunar Lunar ARTS. The chassis was constructed of AISI 1008 steel rod because of its strength and it's easy to work with.

8.4 Suspension

8.4.1 Introduction

The Lunar ARTS proposed is unique in the fact that it will articulate between each pair of wheels. Although this will increase the manuverability of the vehicle it will also be unstable platform to opperate from. Because of the unstability of this design a model was constructed to study the possible problems that are related to the two-wheeled vehicle.

8.4.2 Constraints

The model's suspension was based on a 1/4 scale of the proposed lunar Lunar ARTS. The main objective was to study the reactions of the Lunar ARTS under certain terain conditions. The basic dimensions were scaled to 1/4 of the full size Lunar ARTS. The final factor for the suspension was the spring and damping constant. This was found once the final weight of the model was determined. Other constraints that were considered were the size of the steering servos and the motors and gear boxes. The wheels were to be driven from the hub and therefore all of the hardware had to be located at the spindle of the Lunar ARTS. This lead to the unique problem of having the relatively large mass at the end of the suspension system.

8.4.3 *Suspension Design Summary*

A double wishbone suspension system was used for four main reasons. First this suspension system will allow the wheel to remain perpendicular to the surface it is riding on. This is very important to maximize the efficientcy of the wheel design. Second this suspension will allow for independent motion of each wheel which will also improved the efficiency. Third this system will allow the least amount of vibration to be transferred from the riding surface to the main chassis and the equipment on board. Finally, this suspension system has been proven over time and is now accepted as a conventional suspension design.

8.5 Steering System

8.5.1 *Introduction*

In order to simulate the proposed Lunar ARTS the axis of rotation of each wheel must be capable of rotating or "turning". To do this steering servos will be located at each hub of the drive wheels. The hub must also contain the drive motors for each wheel.

8.5.2 *Constraints*

The steering servos must be close to the hub of each drive wheel and be able to turn each wheel in the worst lunar surface conditions. The motors must have enough power to simulate the maximum speed and have enough torque to propel the vehicle up the steepest grade with a full design load which is given in the design constraints of the proposed Lunar ARTS.

8.5.3 *Steering and Drive Systems*

To achieve the designed turning radius servos were bolted to the bottom hub plate. These servos are controlled by a radio unit and are in commonly used in remote controlled models.

The wheels are driven by geared down electric motors. The motors attach to the back of the hub plate. On the output shaft of the motors a small pinion sprocket is attached to drive the large sprocket which is attached to the rear of the hubs.

Power will be provided by battery packs located on the second cart. Note that an external charger must be used in order to restore the batteries to there design voltage.

8.6 Navigation and Communication

8.6.1 *Introduction*

The simulation of the navigation and communication system was hampered by the cost and complexity of even the simplest configurations. What was eventually attempted was a simulation of the remote mode where a limited number of control signals would be transmitted to the remote station. This enabled illustration of two of the most important functions of the navigation and communication systeme.

8.6.2 *Remote Mode With Stereo Vision*

To simulate the ability of the Lunar ARTS to be controlled from a lunar base via a stereo vision image provided by cameras on the Lunar ARTS, a 8mm camcorder/monitor combination was used. The camcorder was mounted at the fore of the Lunar ARTS, and a trailing co-axial cable connected it to the monitor at the remote station. This provided a 'virtual environment' for the operator. A co-axial cable had to be used as a video transmitter cost $4000.

8.6.3 Control Signal Transmission

To simulate the transmission of signals for control and feedback information, sensors were used to detect information such as wheel angle of deflection, wheel angle of turn, angle of roll, velocity, and battery level. Also, a range finder was used to provide information that could be incorporated with the camera to provide true stereo vision. The model just displayed the range to object after being transmitted to the remote station. All the signals were analog, with the exception of the range finder which was converted to analog. They were multiplexed and converted to a frequency by a V/F converter, then sent over FM to the remote station. Then they were converted again by a F/V converter and input into an IMB PC clone via an ADC. An interactive program displayed the various signals as they might appear in the astronaut's helmet.

Appendix A. Project Completion and Lunar ARTS Design Constraints

A.1 Project Completion

A.1.1 Gantt Chart

Fig. A.1 shows the Gantt chart for the project.

A.1.2 Individual Responsibilities Chart

Fig. A.2 shows the breakdown of each individuals' responsibilities for the completion of the vehicle.

A.1.3 Class timeline

Fig. A.3 shows the contents of each week's meeting agenda for the second semester.

A.2 Individual Cart Mass Breakdown

The following is a program to determine the total mass of each individual cart as well as a total mass of the vehicle. Data input can be by either keyboard, or by data file. If entry is by keyboard, then the data will be written to a file for input for next run of the program. Output is a breakdown on each cart (by component) of the masses. Listed below is the fortran program.

```
c  This program is written to determine the mass of the
c lunar articulated Remote Transportation  System Vehicle
c
c  This program will allow the user to enter in the data
c from the keyboard or from a data file, and the output
c will be a data file.
c
c  Each cart will be treated separately and a total mass for
c all three carts will be calculated as well as
c the "emergency" mass in the event that the last cart has to
c be disconnected in an emergency.
c
c  This program was last modified on January 26, 1990
c
c ******************************************************
c Variables
c chas=chassis
c susp=suspension
c stee=steering assembly
c trac=traction drive assembly
c whee=wheel assembly
c driv=drive control assembly
c seat=seats
c came=camera and lighting assembly
c prot=protection equipment (meteoroid) and other
c miscellaneous equipment
c tool=tools and scintific equipment
c moto=motors
```

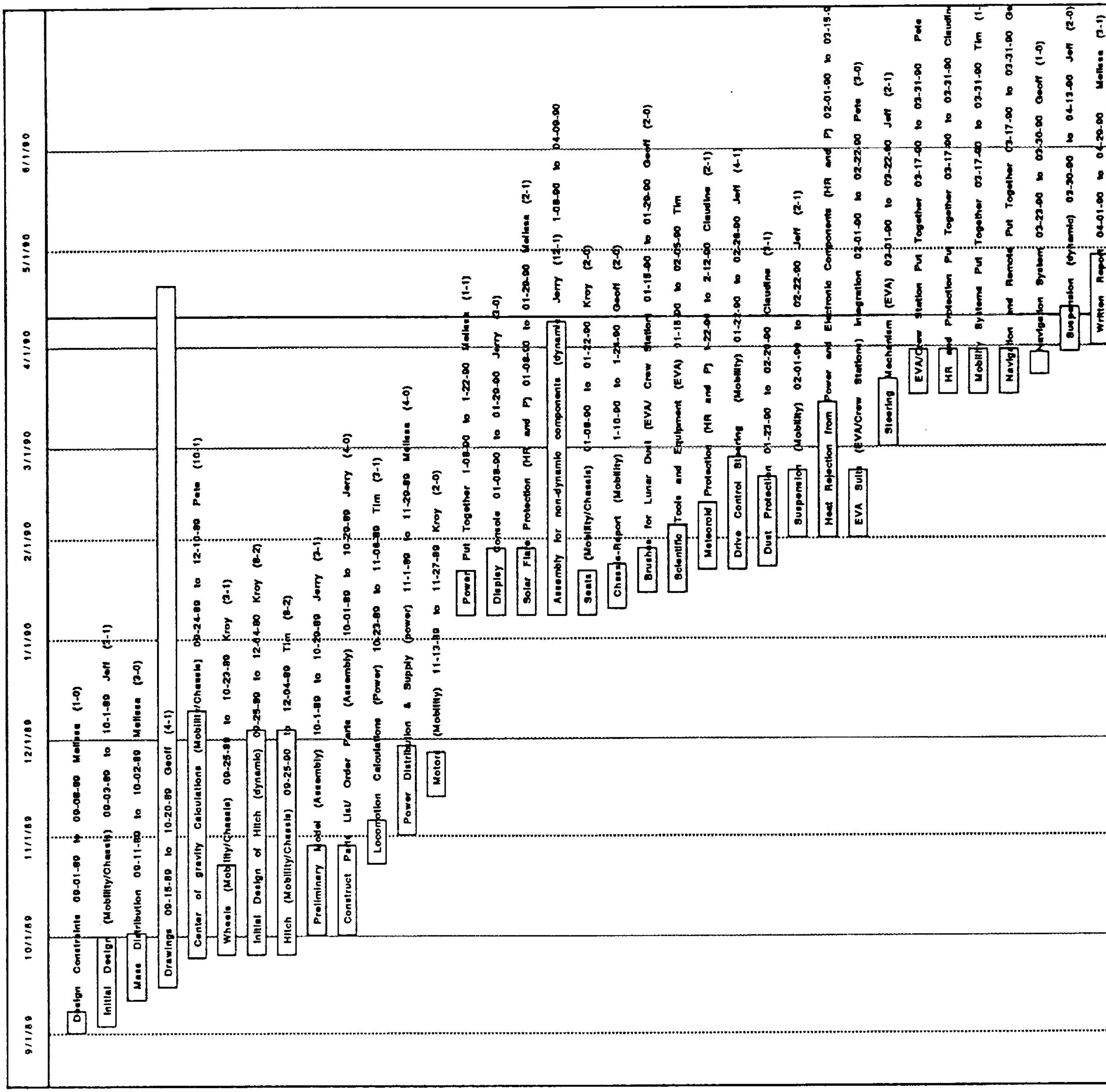

Figure A.1. Gantt chart for project.

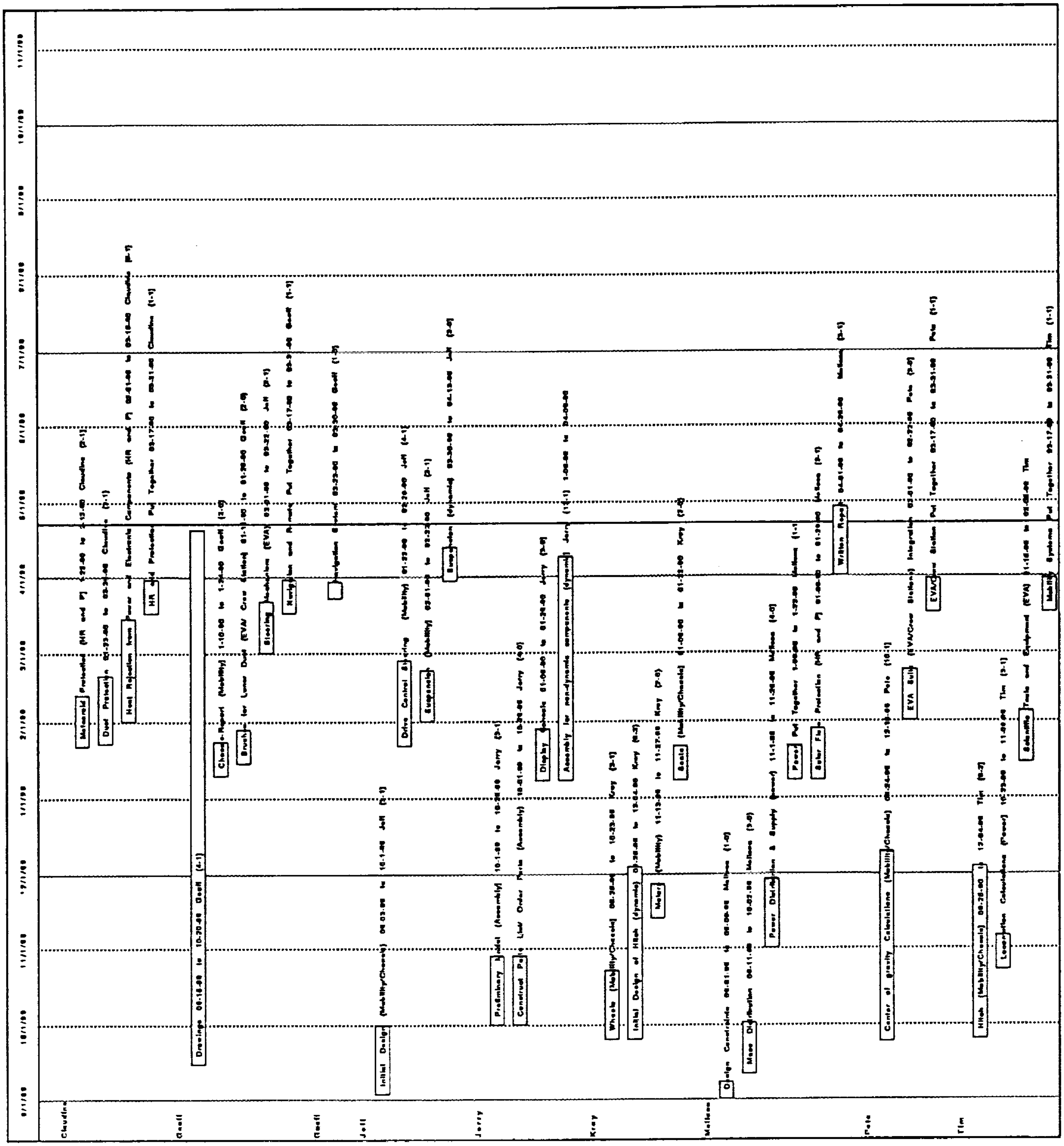

Figure A.2. Individual responsibilities for vehicle components.

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	January 11	18	25	February 1	8	15	22	March 1	8	15	22	29	April 5	12	19	26
Critical Design reviews for all components completed in the first semester.		X														
All Final Reports are due from the first semester in the pre-set TEX format form for the final report				X							Spring break					
Formal Presentation to Faculty of components completed up to this point. Check on status of dynamic and full-scale model. All written material (Tex reports) to be turned in by following week with corrections.							X					X				
Initial Dynamic Model Review. Rolling chassis to be completed.							X									
Written Report put together and final review for all systems.													X			
Discussion and wrap-up for final oral presentation for both full-scale and dynamic model. Final dicussion on oral report. EVERYTHING SHOULD BE COMPLETED.													X			
Final presentation of report to faculty														X		
Final written report delivered to faculty and final dynamic model turn-in.															X	
Subcritical reviews of components completed to this point. Hardbound notebooks to be turned in after this presentation.		X		X		X		X		X		X				
Status report of systems to be completed and status of written reports by all individuals			X		X		X		X			X				
Systems integration of components		X	X	X	X	X		X	X	X			X			
Report by all systems component managers			X			X			X							

Figure A.3. Meeting agendas for the second semester.

```
c comp=computer and control display
c navi=navigation equipment (stereo vision)
c comm=communication equipment and drive control electronics
c men=men and their EVA suits and supporting equipment
c ligh=lighting
c fuel=fuel cell stacks
c ener=energy storage system
c heat=heat rejection systems
c payl=payload
c mt1f=total mass for cart 1 for full operational mode
c mt2f=total mass for cart 2 for full operational mode
c mt3f=total mass for cart 3 for full operational mode
c mtf=total mass of carts for full operational mode
c mob=mobility subsystem - chassis=(susp+trac+whee+driv)
c
c NOTE: Since there are three carts the chassis of each cart
c will be denoted as chas1, chas2, chas3, etc... This will
c also hold true for the protection
c
c ************************************************************
c
c  declare all variables
c
real chas1,chas2,chas3,susp,trac,whee,driv,seat,
     + came,prot1,prot2,prot3,tool,moto,comp,navi,comm,
     + men,ligh,fuel,ene,heat,payl,mt1f,mt2f,mt3f,
     + mt1e,mt2e,mt3e,mtf,mte,mob
integer m,in
c
c  open file
c
open(1,file='mass.out',status='new',carriage control='list')
c
c  explain the program to the user
c
print*,'The purpose of this program is to determine the total mass'
print*,'  of the lunar articulated remote transportation system. The'
print*,'  user will have the option of entering in data from the'
print*,'  keyboard or from a data file. If entering in a data file the'
print*,'  user will be given an explanation of the format of the'
print*,'  input data file. The data file should be named "MASS.DAT"'
print*,'  All numbers are in Kilograms and and are entered as XX.XX'
print*
print*,'Output will be done by an output file called "mass.out"'
print*
print*,'The user will be given a final output of the total'
print*,'  mass for both full operation of the vehicle and for'
print*,'  emergency operation of the vehicle (a case in which the'
print*,'  last cart will be attached so as to decrease the total'
print*,'  weight of the vehicle in the event an emergency return'
```

```
print*,'  was desired.)'
print*,'The carts of the vehicle are as follows:'
print*,' cart 1-Men, Tools, Navigation, and Computers'
print*,' cart 2-Power System'
print*,' cart 3-Payload carrier'
print *
print *,'It is assumed that the mobility system on all three '
print*,'carts are the same with the exception of the chassis'
print*,'and the seats.'
c
c  Data input by file of keyboard?
c
print*,'Will data be read from keyboard=1 or datafile=2?'
read (*,*)in
if (in.eq.2)then
open (2,file='mass.dat',status='old')
else if (in.eq.1)then
open (2,file='mass.dat',status='new')
end if
c
c  Enter in the data for cart 1
c
print*,'The mass of the first cart will be calculated'
print*
c
c   If input is from data file
c
if (in.eq.2)then
print*,'The input format for the data file should include the mass'
print*,'  of the vehicle (real numbers) in the following order:'
print*,'  Chasssis,Suspension,Steering Assembly, Traction Drive '
print*,'  Assembly,Wheel Assembly, Drive Control Assembly,Seats'
print*,'  Camera and Lights, Protection Equipment'
print*,'  (meteoroid)and other, 2 Motors,'
print*,'  Computer and Control Display,Navigation Equipment(stereo'
print*,'  vision),Communication Equipment(drive control electronics),'
print*,'  2 Men and EVA suits, and Lights.'
read(2,*)chas1,susp,stee,trac,whee,driv,seat,came,prot1,moto,comp,
     + navi,comm,men,ligh
c
c if input is by keyboard
c
else if (in.eq.1) then
print*,'Input all masses in Kilograms for cart 1'
print*,'Input chassis'
read(*,*)chas1
write (2,*)chas1
print*,'Input Suspension'
read(*,*)susp
write (2,*)susp
```

```
print*,'Input Steering Assembly'
read(*,*)stee
write(2,*)stee
print*,'Input Traction Drive Assembly'
read(*,*)trac
write(2,*)trac
print*,'Input Wheel Assembly'
read(*,*)whee
write(2,*)whee
print*,'Input Drive Control Assembly'
read(*,*)driv
write(2,*)driv
print*,'Input Seats'
read(*,*)seat
write(2,*)seat
print*,'Input Camera and Lights'
read (*,*)came
write(2,*)came
print*,'Input Protection Equipment (meteoroid) and other'
read(*,*)prot1
write(2,*)prot1
print*,'Input 2 Motors'
read(*,*)moto
write(2,*)moto
print*,'Input Computer and Control Display'
read(*,*)comp
write(2,*)comp
print*,'Input Navigation Equipment (Stereo Vision)'
read(*,*)navi
write(2,*)navi
print*,'Input Communication Equipment and Drive Control Electronics'
read(*,*)comm
write(2,*)comm
print*,'Input Mass of 2 men,EVA Suits & Supporting Equip.'
read(*,*)men
write(2,*)men
print*,'Input Directional Lighting'
read(*,*)ligh
write(2,*)ligh
end if
20 print*
c
c  Calculate the total mass of cart 1
c
mob=susp+stee+trac+whee+driv
mt1f=chas1+mob+seat+prot1+moto+came+comp+navi+men+comm+ligh

c
c  Enter in data for cart 2
c
```

```
print*,'The mass of the second car will be calculated'
print*
c
c if input is from the data file
c
if(in.eq.2)then
print*,'The input format for the data file should continue by'
print*,'  having the following masses in order for cart 2.'
print*,'  The data should be a continuation of mas.dat where'
print*,'  the data for cart 2 follows data for cart 1'
print*
print*,'Assuming that in the mobility system (chassis,suspension,'
print*,'  traction drive assembly, wheel assembly and drive control,'
print*,'  assembly) will be the same for all three carts with the'
print*,'  exception of the chassis, the following information will'
print*,'  be read in the following order: Chassis, Fuel cell stack,'
print*,'  Energy storage system, Heat rejection system, and Protection'
print*,'  (meteoroid) and other.'
read(2,*)chas2,fuel,ener,heat,prot2
c
c If input is by keyboard
c
else if(in.eq.1)then
print*,'Input Chassis'
read(*,*)chas2
write (2,*)chas2
print*,'Input Fuel cell stack system'
read(*,*)fuel
write(2,*)fuel
print*,'Input Energy storage system'
read(*,*)ener
write(2,*)ener
print*,'Input Heat rejection systems'
read(*,*)heat
write(2,*)heat
print*,'Input Protection (meteoroid) and other'
read(*,*)prot2
write(2,*)prot2

end if
40 print*
c
c  Calculate mass of cart 2
c
mt2f=chas2+mob+fuel+ener+heat+prot2+moto
c
c  Enter in data for cart 3
c
print*,'The mass of the third cart will be calculated'
print*
```

```
c
c if data in by file
c
if(in.eq.2) then
print*,'The input format the for data file should continue by'
print*,'  having the following masses in order for cart 2. The'
print*,'  data should be a continuation of mass.dat where the data'
print*,'  for cart 2 follows the data for cart 1'
print*
print*,'Assuming that the mobility systems are the same for cart 3'
print*,'  as for cart 2 (with the exception of the chassis), the'
print*,'  data should be arranged in the following order: Chassis,'
print*,'  protection(meteoroid) and other, Tools and Scientific'
print*,'  equipment, and Payload.'
read(2,*)chas3,prot3,tool,payl
c
c if data is read in by keyboard
c
else if (in.eq.1)then
print*,'Input Chassis'
read(*,*)chas3
write(2,*)chas3
print*,'Input Protection (meteoroid) and other'
read(*,*)prot3
write(2,*)prot3
print*,'Input Scientific Tools and Equipment'
read(*,*)tool
write(2,*)tool
print*,'Input Payload Requirement'
read(*,*)payl
write(2,*)pay1
end if
60 print*
c
c  Calculate the mass of the third cart
c
mt3f=chas3+mob+tool+prot3+payl
c
c  Output data for both the full operation and emergency case
c
mtf=mt1f+mt2f+mt3f
c
c printout header
c
write (1,100)
100 format(/,'Cart 1 - Men, Navigation and Computers')
write (1,200)
200 format(/,'Cart 2 - Power Systems')
write (1,300)
300 format(/,'Cart 3 - Payload Carrier and tools')
```

```
write (1,550)
550 format(///,2X,'Description',t60,'Mass (kilograms)')
c
c printout cart 1 information
c
write (1,600)
600 format(/,'CART 1 - Men, Navigation, and Computers')
write (1,610)
610 format(/,'Mobility System')
write (1,650)chas1
650 format(5x,'Chassis',t60,f9.2)
write (1,660)susp
660 format(5x,'Suspension',t60,f9.2)
write(1,670)stee
670 format(5x,'Steering Assembly',t60,f9.2)
write(1,680)trac
680 format(5x,'Traction Drive Assembly',t60,f9.2)
write (1,690)whee
690 format(5x,'Wheel Assembly',t60,f9.2)
write(1,700)driv
700 format(5x,'Drive Control Assembly',t60,f9.2)
write(1,710)seat
710 format(5x,'Seats',t60,f9.2)
write (1,712)came
712 format (5x,'Camera and Lights',t60,f9.2)
write(1,730)prot1
730 format('Protection(meteoroid) and other',t60,f9.2)
write(1,750)moto
750 format('2 Motors',t60,f9.2)
write (1,760)comp
760 format('Computer and Control Disply',t60,f9.2)
write (1,770)navi
770 format('Navigation Equipment',t60,f9.2)
write (1,775)
775 format('Communication Equipment')
write(1,780)comm
780 format(2x,'& Drive Control Electronics',t60,f9.2)
write(1,790)men
790 format('2 men, EVA Suits, and supporting equipment',t60,f9.2)
write (1,800)ligh
800 format('Directional Lighting and Hardware',t60,f9.2)
write (1,850)mt1f
850 format(/,'Total mass on cart 1 (full operating conditions) is ',
     + f9.2,' kgs')
c
c print out information on cart 2
c
write (1,1000)
1000 format(///,'CART 2 - Power Systems')
write (1,1100)
```

```
1100 format(/,'Total of mobility system without')
write (1,1200)mob
1200 format(2x,'chassis and seats',t60,f9.2)
write (1,1300)chas2
1300 format(5x,'Chassis',t60,f9.2)
write(1,1350)moto
1350 format('2 Motors',t60,f9.2)
write (1,1400)
1400 format('Fuel Cell System')
write (1,1500)fuel
1500 format(5x,'Fuel Cell Stacks',t60,f9.2)
write (1,1550)ener
1550 format(5x,'Energy Storage Systems',t60,f9.2)
write (1,1600)heat
1600 format (5x,'Heat Rejection System',t60,f9.2)
write (1,1650)prot2
1650 format ('Protection(meteoroid and thermal)',t60,f9.2)
write(1,1800)mt2f
1800 format(/,'Total mass for cart 2 (full operating conditions) is ',
     + f9.2,' kgs')
c
c printout cart 3 masses
c
write (1,2000)
2000 format(///,'CART 3 - Payload carrier and tools')
write (1,2010)
2010 format('Total of mobility system without')
write (1,2020)mob
2020 format(2x,'chassis and seats',t60,f9.2)
write(1,2030)chas3
2030 format('Chassis',t60,f9.2)
740 format('Tools and Scientific Equipment',t60,f9.2)
write(1,740)tool
write (1,2050)payl
2050 format('Payload',t60,f9.2)
write (1,2060)prot3
2060 format('Protection(meteoroid) and other',t60,f9.2)
write (1,2070)mt3f
2070 format(/,'Total mass of cart 3 : full operating conditions is ',
     + f9.2,' kgs')
c
c Total mass of vehicle
c
write (1,3000)
3000 format (//,'Total mass of vehicle in full operating condition is ')
write (1,3010)mtf
3010 format (f9.2,' kgs')
stop
end
```

Listed below is the output file of the mass program.

```
Cart 1 - Men, Navigation and Computers

Cart 2 - Power Systems

Cart 3 - Payload Carrier and tools



  Description                                                 Mass (kilograms)

CART 1 - Men, Navigation, and Computers

Mobility System
     Chassis                                                     32.43
     Suspension                                                  11.60
     Steering Assembly                                            2.00
     Wheel Assembly                                              22.50
     Drive Control Assembly                                       4.76
     Seats                                                        6.93
     Camera and Lights                                           30.00
Protection(dust)                                                 35.00
2 Motors                                                         12.00
Computer and Control Disply                                       3.80
Navigation Equipment                                             22.00
Communication Equipment
  & Drive Control Electronics                                    30.00
2 men, EVA Suits, and supporting equipment                      470.00
Directional Lighting and Hardware                                20.00

Total mass on cart 1 (full operating conditions) is    703.02 kgs



CART 2 - Power Systems

Total of mobility system without        70.86
  chassis and seats
     Chassis                                                     32.43
2 Motors                                                         12.00
Fuel Cell System
     Fuel Cell Stacks                                            85.00
     Heat Rejection System and Energy Storage Systems           152.30
Protection(solar and thermal)                                    40.00

Total mass for cart 2 (full operating conditions) is    392.59 kgs
```

```
CART 3 - Payload carrier and tools
Total of mobility system without
  chassis and seats                                            70.86
Chassis                                                        32.43
Tools and Scientific Equipment                                100.00
Payload                                                       750.00
Protection(meteoroid) and other                                30.00

Total mass of cart 3 : full operating conditions is    983.29 kgs


Total mass of vehicle in full operating condition is
  2079.08 kgs
```

Appendix B. Power

B.1 Power Calculation

B.1.1 Locomotion Energy Calculations

The locomotion program provides a step by step process and explanation of all parameters and logistics for calculating locomotion energy for the Lunar ARTS. Note the output files for the desired information.

```

C                    LOCOMOTION ENERGY PROGRAM FOR THE LRV
C                              By: Timothy R. DiMella
C
C              ****************************************************************
C              ****This is an updated program. The report itself varies
C              ****little to the results of this updated program. Mass
C              ****requirements for each cart was changed at the last
C              ****minute. Because cart 2 is proposed as weighing so little,
C              ****a system of contact areas is itself proposed. No longer
C              ****will the ground contact length be so similar for each
C              ****wheel. Note as well that the locomot.dat energy requirement
C              ****output file is different than the result in the paper. Refer
C              ****to 'UPDATE' in this program for changes.
C              ****************************************************************
C
C           [THIS PROGRAM PERMITS RAPID CALCULATION OF THE ENERGY
C            AND POWER REQUIREMENTS FOR LOCOMOTION OF THE LUNAR ROVER
C            VEHICLE (LRV) TAKING INTO ACCOUNT EACH COMBINATION OF
C            SOIL TYPE AND SLOPE ON THE LUNAR SURFACE.]
C
C
C
C Di   Wheel Diameter (m)
C Si   Wheel spring (deflection) stiffness (N/m)
C ton  Tonnage on each wheel (lbf)
C phi  Angle of friction (degrees)
C kphi Friction modulus of deformation (lbf/(in**n+2)
C kc   Cohesive modulus of deformation (N/(m**n+1)
C        n    Exponent of sinkage
C        gma  Soil density (N/cubic meter)
C K    Slip coefficient
C thta Slope (radians)
C        Wi   Weight of each wheel (N)
C        WT   Total amount of wheels used on each cart
C        C    Cohesion
C        bta  Angle of soil rupture (degrees)
C        dse  Drive System Efficiency
C        dte  Drive Train Efficiency
C        DET  Total Damping energy experimentally 25% EXT (kw-h/km)
C        GE   Locomotion energy recalculated wrt dse (kw-h/km)
```

```
C        GET  Total locomotion energy of each cart (kw-h/km)
C        LET  Sum of total static and damping energies (kw-h/km)
C        T    Percentage of distance traveled wrt slope thta (decimal)
C        upper  upper bound for thrust (N)
C        lower  lower bound for thrust (N)
C        su     upper bound for slip   (fraction)
C        sl     lower bound for slip   (fraction)
C        LE,EXT net static energies (kw-h/km)
C        ttt  total power cart 1 for men and supplies (kw)
C        uuu  total power cart 2 for fuel cells (kw)
C        vvv  total power cart 3 (kw)
C        TPOW total power for LRV (kw)
C
C      ALL INTEGERS AND REAL NUMBERS ARE EXPLAINED WITHIN THE PROGRAM.
C
       integer   count, WT, I, J, X, F, flag, MM, NN, CART
       real  Wni, Wi, thta, Dlt, Si, li,bi,ai,pi,Lii,BF,Aii,Pii,Rr,Rb,
     *      Rc,Rg,Rt,H,Di,Bii,fi,phi,C,kphi,kc,n,gma,K,Pcrit,
     *      za,zb,RrT,bta,RbT,RcT,s,
     *      dte,E(5),DET,LE,dse,GE,GET,res,
     *      THRUST(1000),LET, power(5),ttt,UUU,VVV
C
C
C      *ASSUME UNIFORM LOADING WHERE NOMINAL WEIGHT FOR EACH WHEEL IS EQUAL.
C      *SI UNITS ARE USED HERE (NOTE HOWEVER THAT Rt MUST BE CONVERTED BACK
C       TO STANDARD UNITS FOR THE ENERGY EQUATION.
C      *REFER TO LOCOMOTION ENERGY SECTION AND REFERENCE SECTION FOR VALIDATION
C       OF ALL PARAMETERS.
C
C   'UPDATE'
C      *BECAUSE EXPERIMENT ON THE WHEEL IS NOT POSSIBLE HERE, 1000 lunar lbf
C       IS ASSUMED TO GIVE A WHEEL CONTACT LENGTH OF 1.0 meter FOR A 2.3 meter
C       DIAMETER WHEEL. AS WELL, IT IS ASSUMED THAT THE WEIGHT ON EACH WHEEL
C       Wi, IS PROPORTIONAL TO THIS LENGTH. I.E. FOR Wi=800 lbf, MULTIPLY
C       1.0 meter x (800/1000) or li=Lii=0.8 meter GROUND CONTACT LENGTH.
C       WHEN EXPERIMENT IS POSSIBLE, BEST BET IS TO TRY TO MATCH THE WEIGHT
C       TO CONTACT LENGTH AND/OR DERIVE YOUR OWN EMPIRICAL FORMULAS FOR THE
C       LARTS' WHEEL.
C
C                                            'locomo.dat' gives slip vs thrust.
      OPEN (1,file='locomo.dat',status='new',carriagecontrol='list')
C
C                                            'locomot.dat' gives energies on 14
C                                             different slopes, total energies,
C                                             and total power for each cart. It
C                                             then gives total power for the LRV.
C                                             Refer Table 1-2.
      OPEN (2,file='locomot.dat',status='new',carriagecontrol='list')
C
C
```

```
C
      flag = 1
      DO 1000 CART = 1,3
C                                       J allows for the soil types to
C                                       be handled separately for dif-
C                                       ferent slope angles in each
C                                       soil category. See Below.
      DO 235 J = 1,4
C
C     1. Calculate wheel normal loading for each wheel:
C
C                                       CART secures evaluation of carts
C                                       1, 2, 3 in sequence. After the
C                                       total energy for cart 1 is calcu-
C  'UPDATE'                             lated, cart 2 is evaluated, then
C                                       cart 3.
      IF (CART .EQ. 1) THEN
        Wi = 574.719
      ENDIF
C
      IF (CART .EQ. 2) THEN
        Wi = 296.417
      ENDIF
C
      IF (CART .EQ. 3) THEN
        Wi = 779.315
      ENDIF
C                                       Refer Table 1-1. J corresponds to
C                                       the five soil types. The fourth and
C                                       fifth soil types are combined
C                                       because kphi and n are the same. MM
C                                       and NN are Do Loop parameters to
C                                       obtain proper slope values in each
C                                       soil type category. Refer Do Loop
C                                       below.
      IF (J .EQ. 1) THEN
MM=1
NN=5
        n=0.5
        K=0.01016
      ENDIF

      IF (J .EQ. 2) THEN
MM=5
NN=6
        n=0.75
        K=0.01016
      ENDIF
c
      IF (J .EQ. 3) THEN
```

```
MM=10
NN=14
          n=1.0
          K=0.01016
        ENDIF
C
        IF (J. EQ. 4) THEN
MM=25
NN=26
          n=1.0
          K=0.00889
        ENDIF
C
        DO 150 XX = MM,NN
C                                                 Note for the first soil type:
C                                                 Loose Dust. From above, MM = 1
C                                                 and NN = 5. This means the first
C                                                 soil type will be calculated 5
C                                                 times for slope angles 0-4 degrees.
C           The first time through, thta = 0;
C                                                 The second time thta = 1;
C                                                 The third time thta = 2; and so on.
C                                                 These values correspond to the
C                                                 angles in Table 1-1. This procedure
C                                                 applies to the rest of the
C                                                 angles in the following J soil
C                                                 type categories in Table 1-1. There
C                                                 are 14 angles. Kphi is entered here
C                                                 because it is changed to metric
C                                                 below before each do loop starts.
        IF (J .EQ. 1) THEN
thta = XX - 1.0
          kphi=0.5
        ENDIF
C
        IF (J .EQ. 2) THEN
thta = MM/1.0
          kphi=1.0
        ENDIF
C
        IF ((J .EQ. 2) .AND. (XX .EQ. 6)) THEN
          thta = XX + 1.5
          kphi=1.0
        ENDIF
C
        IF (J .EQ. 3) THEN
thta = MM/1.0
          kphi =3.0
        ENDIF
C
```

```
      IF ((J .EQ. 3) .AND. (XX .EQ. 11)) THEN
thta = XX + 1.5
        kphi=3.0
      ENDIF
C
      IF ((J .EQ. 3) .AND. (XX .EQ. 12)) THEN
thta = XX + 3.0
        kphi=3.0
      ENDIF
C
      IF ((J .EQ. 3) .AND. (XX .EQ. 13)) THEN
thta = XX + 4.5
        kphi=3.0
      ENDIF
C
      IF ((J .EQ. 3) .AND. (XX .EQ. 14)) THEN
        thta = XX + 6.0
        kphi=3.0
      ENDIF
C
      IF (J .EQ. 4) THEN
        thta = MM/1.0
        kphi = 6.0
      ENDIF
C
      IF ((J .EQ. 4) .AND. (XX .EQ. 26)) THEN
        thta = XX + 4.0
        kphi=6.0
      ENDIF
C                                           T corresponds to the percent of
C                                           total distance traveled for each
C                                           slope in Table 1-1.
      IF (thta .EQ. 0.0) THEN
         T = 0.11
      ENDIF
      IF (THTA .EQ. 1.0) THEN
         T = 0.225
      ENDIF
      IF (THTA .EQ. 2.0) THEN
         T = 0.245
      ENDIF
      IF (THTA .EQ. 3.0) THEN
         T = 0.16
      ENDIF
      IF (THTA .EQ. 4.0) THEN
         T = 0.1
      ENDIF
      IF (THTA .EQ. 5.0) THEN
         T = 0.075
      ENDIF
```

```
      IF (THTA .EQ. 7.5) THEN
         T = 0.03
      ENDIF
      IF (THTA .EQ. 10.0) THEN
         T = 0.018
      ENDIF
      IF (THTA .EQ. 12.5) THEN
         T = 0.012
      ENDIF
      IF (THTA .EQ. 15.0) THEN
         T = 0.01
      ENDIF
      IF (THTA .EQ. 17.5) THEN
         T = 0.005
      ENDIF
      IF (THTA .EQ. 20.0) THEN
         T = 0.005
      ENDIF
      IF (THTA .EQ. 25.0) THEN
         T = 0.003
      ENDIF
      IF (THTA .EQ. 30.0) THEN
         T = 0.002
      ENDIF
C                                          Note that Fortran will only
C                                          allow for radians in calculations
C                                          of trigonometric functions.
       thta = thta * 3.1415927 / 180
        Wni = Wi * cos(thta)
       print*,'Wni ',Wni
C
C     2. Calculate average ground pressure under each wheel (5 parts):
C        The following must be either hypothetical or experimental.
C
C     Si=xxx (must be done experimentally)
      Di=2.3
C
C       a. Calculate wheel deflection (N/m):
C              Dlt = Wni / Si
C
C    'UPDATE'
C       b. Calculate ground contact length (m):
         IF (cart .EQ. 1) then
         li = 0.6
         ENDIF
         IF (CART .EQ. 2) THEN
         li = 0.3
         ENDIF
         IF (CART .EQ. 3) THEN
         li = 0.8
```

```
          ENDIF
C
C       c. Calculate ground contact width (m):
              bi = 0.75
C
C       d. Calculate ground contact area (sq. m):
              ai = bi * li
C
C       e. Calculate average ground pressure (N/sq. m):
              pi = Wni / ai
C
      PRINT*,Dlt,li,bi,ai,pi
C     3. Calculate maximum allowable critical ground pressure:
C
       kphi = kphi/(2.54**2.5)*(100**2.5)*4.448
C
      print*,'kphi ',kphi
      Pcrit = (Wni*(n+1)) / (bi*(3.0*Wni/((3.0-n)*bi*kphi*sqrt(Di)))
     #  **(1.0/(2.0*n+1.0))) * sqrt(Di-(3.0*Wni/((3.0-n)*bi*kphi
     #  *sqrt(Di)))**(2.0/(2.0*n+1.0)))
      print*,'Pcrit ',Pcrit
C
C     If Pcrit is greater than pi as calculated in step 2.e, the wheel can be
C      considered flexible: if Pcrit is less than pi then rigid wheel equations
C      must be considered. The wheel should be designed therefore assumed
C      flexible.
C
C     4. Calculate wheel sinkage (7 parts):
C                                                  Refer Table 1-1.
      kc=0.0
C
C       a. In the first approximation, calculate sinkage for either flexible
C        or rigid wheel
C
        print*,'pcrit ',Pcrit
C                                                  Pcrit should be GT pi from above.
 50     If (Pcrit .GT. pi) then
          za = (pi/(kc/bi + kphi))**(1.0/n)
        endif
C
 60     If (Pcrit .LT. pi) then
          za = (3.0*Wni/((3.0-n)*(kc+bi*kphi)*sqrt(Di)))**(2.0/
     *            (2.0*n+1.0))
      endif
      PRINT*,'za is ',za
C                                                 Refer to Locomotion Energy Section
C                                                 in LRV report for determining
C                                                 correct ground contact length and
C                                                 ground contact width.
      count = 1
```

```
C
C  'UPDATE'
C      b. Correct ground contact length because of addition contact
C        length due to sinkage
              IF (CART .EQ. 1) THEN
              Lii = 0.6
              ENDIF
              IF (CART .EQ. 2) THEN
              Lii = 0.3
              ENDIF
              IF (CART .EQ. 3) THEN
              Lii = 0.8
              ENDIF
C
C      c. Correct ground contact width:
              BF = 0.75
C
C      d. Recalculate ground contact area:
             Aii = Lii * BF
C
C      e. Recalculate average ground pressure:
             Pii = Wni/Aii
C
C      f. Recalculate sinkage using equations above:
C
 70        If (Pcrit .GT. pi) then
              zb = (Pii/(kc/BF + kphi))**(1.0/n)
           endif
C
 80        If (Pcrit .LT. pi) then
              zb = 3.0*Wni/((3.0-n)*(kc+BF*kphi)*sqrt(Di))**(2.0/
     *            (2.0*n+1.0))
           endif
           print*,'zb is: ',zb
C                                               Refer Locomotion Energy Section
C                                               on sinkage. Note that za = zb
C                                               because li and bi are constants.
             If (za .LT. zb) then
               za = za + 0.0
             ENDIF
C
             IF (za .GT. zb) then
               za = zb
             ENDIF
C
C      5. Calculate the rolling resistance Rr for each wheel and sum up
C         for all wheels.
C                                               Refer Locomotion Energy section
C                                               for Rolling Resistance and Assi-
C                                               milation for calculating fi.
```

```
      WT=2.0
C           Rr = fi * Wni (fi Experimental)
C
C                      -OR-
C
            speed=8.0
            psr=1.76
            ton=Wni/4.448/2000
            Rr=5.1 + (5.5+18*ton)/psr + (8.5+6*ton*(speed/100)**2)/psr
C
C                                           Since Rr results in kg from the
C                                           above equation it must be multiplied
C                                           by one-sixth the gravity of earth,
C                                           i.e. 9.81/6.0 = 1.635.
            Rr=Rr*1.635
            RrT = WT * Rr
          print*,'RrT ',RrT
C
C     6. Calculate bulldozing resistance Rb for each wheel and sum up
C        for all wheels.
C
      gma=13571.681
      phi=37 * 3.1415927 / 180
      C=0.0
C
            Rb = 0.5*gma*BF*(za**2)*(tan(0.7854+0.5*phi))**2+2*C*BF*
     #      za*tan(0.7854+0.5*phi)
C
           RbT = WT * Rb
       print*,'RbT ',RbT
C
C     7. Calculate compaction resistance Rc for each wheel and sum up for
C        all wheels.
C
           Rc = BF*(kc/BF + kphi)*(za**(n+1.0))/(n+1.0)
           RcT = WT * Rc
         print*,'RcT ',RcT
C
C     8. Calculate grade resistance Rg for total vehicle.
C
           Rg = Wni * WT * sin(thta)
      print*,'Rg ',Rg
C
C     9. Add totals of RrT, RbT, RcT, and Rg to determine total vehicle
C        steady-state motion resistance.
C
           Rt = RrT + RbT + RcT + Rg
         print*,'Rt ',Rt
C
C     10. Calculate thrust H as a function of slip (2 parts):
```

```
C
C        a. Determine H as a function of slip for each wheel.
C
C                                            K = 0.00889 for compact soil.
C
C                                            K = 0.01016 for loose soil.
C
C                                            The slippage s must be estimated
C                                            corresponding to H = Rt. Because
C                                            an exact s can not be found to
C                                            equal a specific thrust H, the
C                                            interpolation process below must
C                                            be given in order to get s. s is
C                                            given 1000 numerals in succession
C                                            from 0.001 to 1.0 or 0.1% to 100%.
C
C                                            Note the 2* in the thrust equa-
C                                            tion below. Because the slip is
C                                            determined for the full weight of
C                                            the vehicle, H is multiplied by
C                                            2 for 2 tires. This can be done
C                                            because of uniform loading. If this
C                                            is not the case, see Part b below.

         DO 130 I = 1,1000
           s=I/1000.0
           H = 2*(C*Ai + Wni*tan(phi))*(1.0-K/s/Li*(exp(-s*Li/K)))
           thrust(I) = H
 120        If (H .GT. Rt) then
              upper = H
              su = s
              GOTO 140
            ENDIF
            If (H .LT. Rt) then
              lower = H
              sl = s
C             print*,'sl is ',sl
            ENDIF
C                                            Because the thrust equation is an
C                                            exponential equation, the slip
C                                            thrust curve will eventually wind
C                                            up virtually constant (a constant
C                                            thrust). Therefore, when the thrust
C                                            starts repeating itself at H<Rt,
C                                            the slip is interpolated from the
C                                            type of curve already ascertained
C                                            (THIS IS USUALLY A LINEAR INTERPO_
C                                            LATION BECAUSE THE CURVE IS CLOSELY
C                                            LINEAR UP TO THE MAXIMUM THRUST).
C                                            Because an exponential curve, a
```

```
C                                                linear interpolation will give the
C                                                minimum slip and thus the minimum
C                                                energy. If the slip-thrust curve
C                                                repeats itself, this usually means
C                                                a very high energy required for
C                                                the LRV anyway. Increasing the
C                                                ground contact length will resolve
C                                                such high energy requirements. It is
C                                                logical that the ground contact
C                                                width should be increased as well.
                IF (I .NE. 1) then
                 limit=thrust(I)-thrust(I-1)
                  IF (limit .LE. 1.0) then
                    s = sl*Rt/thrust(I)
                    GOTO 145
                  ENDIF
                ENDIF
            print*,'s & H ',s,H
 130         CONTINUE
C             endif
C
C          b. The H versus Slip curve for the complete vehicle is then
C             obtained by adding the separate H values for each wheel
C             at each value of slip.  This results in a thrust versus
C             "average" slip relationship.
C
C       11. Determine average wheel slip.  For steady-state operation
C           the thrust H must equal the total external motion resistance,
C           Rt.  Therefore, knowing Rt for the vehicle from Step 9, the
C           value of slip can be read directly from the Thrust-Slip
C           curve or derived by the DO LOOP in Step 10.a above.
C
C        12. Calculate net steady-state locomotion energy for each
C            slope-soil combination.
C
 140          s = (su-sl)*(Rt - lower)/(upper - lower) + sl
C
C                                                Refer Locomotion Energy Section for
C                                                explanation on drive train effi-
C                                                ciency (dte) and drive system
C                                                efficiency (dse).
 145          dte = 0.95
C
              print*,'s is ',s
C
C               To use the following energy formula, Rt must be converted
C                to Standard Units. E is in kW-hr/km.
C
              Rt = Rt/4.448
C
```

```
              E(flag) = T * 0.00123 * Rt / (dte * (1 - s))
C
C                                              Slippage for 14 slopes encoun-
C                                              tered (in fractional form i.e.
C                                              written:0.01 means:1%) for each
C                                              cart and thrust (equivalent to
C                                              Rt as stated above) is sent to
C                                              locomo.dat for slip-thrust curve
C                                              on each cart.
              Write(1,147) s,Rt
147           format(f5.4,1X,f8.4)
C                                              14 energies corresponding to
C                                              14 different slopes encountered
C                                              will be sent to locomot.dat.
C                                              See below on Flag.
C
              Write(2,148) 'E',flag,' is: ',E(flag)
148           format(A,I2,A,f7.5)
C
C        13. Add net steady-state and damping energies for each soil-slope
C            combination. (Refer Locomotion Energy Section)
C
            IF (FLAG .EQ. 1) THEN
              EXT = 0.0
            ENDIF
C
            EXT = EXT + E(FLAG)
C                                              Flag is a counter for the energy
C                                              required to climb each slope; 14
C                                              in all. Refer Table 1-1.
            flag = flag + 1
150         CONTINUE
C
235         CONTINUE
C
          LE = EXT
          print*,'LE ',LE
          DET = 0.25 * LE
          LET = LE + DET
          print*,'LET ',LET
C
C        14. Determine gross energy due to Rt and damping requirements.  This
C            depends on drive system efficiency, which in turn, depends on
C            the specific drive system.  Dividing the results from Step 19 by
C            the drive system efficiency (dse) gives the gross value of LE.
C
           dse=0.95
C
              GE = LET / dse
              PRINT*,'GE ',GE
```

```
C
C      15. In addition to the factors thus far discussed, energy is also
C          required to accelerate, brake and steer the vehicle, and to
C          overcome losses due to surface roughness.  Since no simple methods
C          are presently available to treat these factors in a rational
C          manner, it is necessary to provide an energy reserve.  At the
C          present time, GM DRL is using a reserve of 35% of the gross energy
C          (GE).  Input reserve into data file.
C
           res=0.35
C
C                                         The total locomotion energy for
C                                         each cart is computed. Note:
C                                         there are two motors on carts 1&2,
C                                         and none on cart 3. (Refer Loco-
C                                         motion Energy Section)
C
           GET = res * GE + GE
           PRINT*,'GET ',GET
C                                         Total locomotion energy per each
C                                         cart is sent to locomot.dat.
C
      write(2,300) 'LOCOMOTION ENERGY CART ',cart,': ',GET,' kw-hr/km'
300   format(A,I1,A,f7.5,A)
C
C          FOR A 75 Km TRIP IN 8 hrs. THE TOTAL POWER FOR 3 CARTS IS:
C
C                                         The total locomotion energy for
C                                         each cart is multiplied by 75 km
C                                         and divided by 8 hrs. to get
C                                         the total locomotion power for
C                                         each cart stored separately.
C                                         (Refer Locomotion Energy Section)
C
           power(cart) = GET * 75.0 / 8.0
C                                         Locomotion Power required for each
C                                         cart is sent to locomot.dat.
C
           write(2,400) 'POWER FOR CART ',cart,': ',power(cart),' kw'
400        format(A,I1,A,f7.3,A)
C
         IF (cart .EQ. 1) then
           ttt = power(cart)
          ENDIF
          IF (cart .EQ. 2) THEN
           UUU = power(CART)
          ENDIF
          IF (cart .EQ. 3) THEN
           VVV = power(cart)
          ENDIF
```

```
C                                              Refer above for the use of Flag.
C                                              After calculation is done on a
C                                              single cart, Flag starts the
C                                              energy process for each slope
C                                              over again.
            FLAG = 1
 1000        CONTINUE
C
C                                              The total locomotion power required
C                                              for the LRV is calculated by adding
C                                              the power of each cart from above.
C
            TPOW = ttt + UUU + VVV
            print*,' '
C                                              The TOTAL LOCOMOTION POWER for the
C                                              LRV is sent to locomot.dat.
C
            write(2,1500) 'TOTAL POWER ALL CARTS: ',TPOW,' kw'
 1500       format(A,f7.3,A)
C
       STOP
       END
```

The following is the output for the locomotion energy program.

```
E 1 is: 0.00161                  LOCOMOT.DAT from the Locomotion
E 2 is: 0.00462                    Energy Calculation Program.
E 3 is: 0.00648
E 4 is: 0.00517                    Based on 25 psi assimilation:
E 5 is: 0.00382
E 6 is: 0.00349            1.  ENERGIES FOR 14 SLOPES ON LUNAR SURFACE
E 7 is: 0.00183
E 8 is: 0.00135            2.  TOTAL ENERGY PER CART
E 9 is: 0.00106
E10 is: 0.00102            3.  TOTAL POWER PER CART
E11 is: 0.00057
E12 is: 0.00063            4.  TOTAL POWER FOR LUNAR ARTS
E13 is: 0.00043
E14 is: 0.00032
LOCOMOTION ENERGY CART 1: 0.05754 kw-hr/km
POWER FOR CART 1:   0.539 kw
E 1 is: 0.00161
E 2 is: 0.00399            ENERGIES DESCEND AS SLOPES ASCEND BECAUSE
E 3 is: 0.00510            TRAVEL PERCENTAGES DECREASE AS SLOPES
E 4 is: 0.00382            INCREASE. REFER TABLE 1-1.
E 5 is: 0.00269
E 6 is: 0.00245
E 7 is: 0.00120
E 8 is: 0.00085
E 9 is: 0.00066
```

```
E10 is: 0.00061
E11 is: 0.00034
E12 is: 0.00037
E13 is: 0.00025
E14 is: 0.00018
LOCOMOTION ENERGY CART 2: 0.04286 kw-hr/km
POWER FOR CART 2:   0.402 kw
E 1 is: 0.00164
E 2 is: 0.00515
E 3 is: 0.00756
E 4 is: 0.00621
E 5 is: 0.00467
E 6 is: 0.00429
E 7 is: 0.00230
E 8 is: 0.00172
E 9 is: 0.00137
E10 is: 0.00132
E11 is: 0.00074
E12 is: 0.00082
E13 is: 0.00057
E14 is: 0.00043
LOCOMOTION ENERGY CART 3: 0.06890 kw-hr/km
POWER FOR CART 3:   0.646 kw

TOTAL POWER ALL CARTS:   1.587 kw
```

B.1.2 Program - Total Power Requirements

The program listed below calculates the total power requirement for the entire Lunar ARTS vehicle. The input may be by data file or by keyboard entry from user. The input of the program is the individual power requirements by each of the components of the vehicle. The data output is to a file and returns a total power requirement that must be supplied to the Lunar ARTS.

```

C     **************************************************************
C
C     **THIS PROGRAM CALCULATES THE POWER FOR THE LUNAR ARTS VEHICLE.**
C                     BY: CLAUDINE DIAZ
C                     DATE: OCTOBER 15,1989
C                     LAST MODIFICATION: JANUARY 21, 1990
C
C     **************************************************************
C     THIS PROGRAM HAS THE OPTION OF INPUTTING DATA FROM THE SCREEN
C     OR FROM AN INPUT FILE. IT CALCULATES THE POWER FOR THE LUNAR ARTS
C     VEHICLE.
C     **************************************************************
C
C
C     *** DECLARE VARIABLES ***
      INTEGER N,M,P,R,Q
```

```
      REAl CCD,CE,DCA,FCS,LE1,LE2,LE3,LIG,TOSC
      REAL LPOWER1,LPOWER2,LPOWER3,MOT1,MOT2,NESV,POWER1
      REAL POWER2,POWER3,STA,CALI,TPOWER1,TPOWER2,TPOWER3,TPOWER
      REAL EPOWER,ERROR
C
C     ***         OPEN OUTPUT FILES                          ***
C
      OPEN (1,FILE='POWER.DAT',STATUS='OLD',CARRIAGECONTROL='LIST')
      OPEN (4,FILE='POWER.OUT',STATUS='NEW',CARRIAGECONTROL='LIST')
C
C     The output of this program is in two files. A list of all
C     the components and the total power is in power.out.

C     ***              DEFINITION OF VARIABLES                   ***
C
C        STA STEERING ASSEMBLY
C      DCA DRIVE CONTROL ASSEMBLY
C CALI CAMARA AND LIGHTS
C        TOSC             TOOLS/SCIENTIFIC EQUIPMENT
C MOT1 2 MOTORS ON CART1
C        MOT2 2 MOTORS ON CART2
C CCD COMPUTER AND CONTROL DISPLAY
C        NESV NAVIGATION EQUIPMENT/STEREO VISION
C CE COMMUNICATION EQUIPMENT AND CONTROL ELECTRONICS
C LIG          DIRECTIONAL LIGHTING WITH HARDWARE
C        FCS FUEL CELL SYSTEM
C        THE LOCOMOTION ENERGY WHICH IS INPUTTED WAS CALCULATED IN A SEPARATE
C        PROGRAM AND INCLUDES 10% POWER LOSS.
C LE1 LOCOMOTION ENERGY CART 1
C LE2 LOCOMOTION ENERGY CART 2
C LE3 LOCOMOTION ENERGY CART 3
C        POWER1 POWER - CART 1 EXCLUDING POWER LOSS
C        POWER2    POWER - CART 2 EXCLUDING POWER LOSS
C POWER3          POWER - CART 3 EXCLUDING POWER LOSS
C LPOWER1 POWER LOSS - CART1
C LPOWER2 POWER LOSS - CART2
C LPOWER3 POWER LOSS - CART3
C        TPOWER1 TOTAL POWER - CART1
C TPOWER2 TOTAL POWER - CART2
C TPOWER3 TOTAL POWER - CART3
C        EPOWER          POWER NEEDED TO MAKE UP FOR EFFICIENCY OF FUEL CELLS
C        ERROR           5% ERROR ADDED TO MAKE UP FOR CHANGES IN FUTURE
C TPOWER TOTAL POWER FOR LUNAR ROVER
C *************************************************************
C
C        *** INPUT DATA ***
C
      PRINT'(///,4X,A)','*POWER CALCULATIONS FOR LUNAR ROVER VEHICLE*'
      PRINT '(//,A)', '     CART 1 - MEN,TOOLS,NAVIGATION,AND COMPUTERS'
      PRINT*, '    CART 2 - POWER SYSTEM '
```

```
      PRINT*, '    CART 3 - PERSONNEL OR REGOLITH CARRIER'
      PRINT'(//,A)',' PRINT ANY NUMBER KEY TO CONTINUE'
      READ(*,*) Q
      PRINT'(A)',' THESE ARE THE VARIABLES FOR WHICH POWER ASSUMPTIONS
     A IN WATTS NEED TO BE INPUTTED'
      PRINT'(/,A)', '        CART 1'
      PRINT*, 'STEERING ASSEMBLY - STA'
      PRINT*, 'DRIVE CONTROL ASSEMBLY - DCA'
      PRINT*, 'CAMARA AND LIGHTS - CALI'
      PRINT*, 'TOOLS/SCIENTIFIC EQUIPMENT - TOSC'
      PRINT*, '2 MOTORS ON CART1 - MOT1'
      PRINT*, 'COMPUTER AND CONTROL DISPLAY - CCD'
      PRINT*, 'NAVIGATION EQUIPMENT/STEREO VISION - NESV'
      PRINT*, 'COMMUNICATION EQUIPMENT AND CONTROL ELECTRONICS - CE'
      PRINT*, 'DIRECTIONAL LIGHTING WITH HARDWARE- LIG'
      PRINT*, 'LOCOMOTION ENERGY- LE1'
      PRINT'(/,A)', '        CART 2'
      PRINT*, '2 MOTORS ON CART 2 - MOT2'
      PRINT*, 'FUEL CELL SYSTEM - FCS'
      PRINT*, 'LOCOMOTION ENERGY- LE2'
      PRINT'(/,A)', '        CART 3'
      PRINT*, 'LOCOMOTION ENERGY - LE3'
C
      PRINT'(/,A)', ' DO YOU WANT TO INPUT DATA FROM THE SCREEN (1) OR
     A FROM A FILE (2)? '
      READ*,  N
      IF (N .EQ. 1) THEN
C   *** INPUT FROM SCREEN ***
      PRINT*,'***ENTER THE POWER IN WATTS***'
      PRINT*,' CART1:'
      PRINT*,'STEERING ASSEMBLY'
      READ*, STA
      PRINT*,'DRIVE CONTROL ASSEMBLY'
      READ*, DCA
      PRINT*,'CAMARA AND LIGHTS'
      READ*, CALI
      PRINT*,'TOOLS/SCIENTIFIC EQUIPMENT'
      READ*, TOSC
      PRINT*,'2 MOTORS'
      READ*, MOT1
      PRINT*,'COMPUTER AND CONTROL DISPLAY'
      READ*, CCD
      PRINT*,'NAVIGATION EQUIPMENT AND CONTROL ELECTRONICS'
      READ*, NESV
      PRINT*,'COMMUNICATION EQUIPMENT/STEREO VISION'
      READ*,CE
      PRINT*,'DIRECTIONAL LIGHTING WITH HARDWARE'
      READ*,LIG
      PRINT*,'LOCOMOTION ENERGY'
      READ*, LE1
```

```
      PRINT '(//,A)',' CART 2:'
      PRINT*, '2 MOTORS'
      READ*, MOT2
      PRINT*, 'FUEL CELL SYSTEM'
      READ*, FCS
      PRINT*, 'LOCOMOTION ENERGY'
      READ*, LE2
      PRINT '(//,A)',' CART 3:'
      PRINT*, 'LOCOMOTION ENERGY'
      READ*, LE3
C
C     WRITE THE DATA INPUTTED THROUGH THE SCREEN TO THE INPUT FILE
      WRITE(1,*)'***ENTER THE POWER IN WATTS***'
      WRITE(1,*)' CART1:'
      WRITE(1,*)'STEERING ASSEMBLY'
      WRITE(1,*) STA
      WRITE(1,*)'DRIVE CONTROL ASSEMBLY'
      WRITE(1,*) DCA
      WRITE(1,*)'CAMARA AND LIGHTS'
      WRITE(1,*) CALI
      WRITE(1,*)'TOOLS/SCIENTIFIC EQUIPMENT'
      WRITE(1,*) TOSC
      WRITE(1,*)'2 MOTORS'
      WRITE(1,*) MOT1
      WRITE(1,*)'COMPUTER AND CONTROL DISPLAY'
      WRITE(1,*) CCD
      WRITE(1,*)'NAVIGATION EQUIPMENT AND CONTROL ELECTRONICS'
      WRITE(1,*) NESV
      WRITE(1,*)'COMMUNICATION EQUIPMENT/STEREO VISION'
      WRITE(1,*)CE
      WRITE(1,*)'DIRECTIONAL LIGHTING WITH HARDWARE'
      WRITE(1,*)LIG
      WRITE(1,*)'LOCOMOTION ENERGY'
      WRITE(1,*) LE1
      WRITE(1,15)' CART 2:'
      WRITE(1,*) '2 MOTORS'
      WRITE(1,*) MOT2
      WRITE(1,*)'FUEL CELL SYSTEM'
      WRITE(1,*) FCS
      WRITE(1,*)'LOCOMOTION ENERGY/REGULAR CONDITION'
      WRITE(1,*) LE2
      WRITE(1,15)' CART 3:'
      WRITE(1,*)'LOCOMOTION ENERGY'
      WRITE(1,*) LE3
   15 FORMAT(/,A)
C
      ELSE
C       ***         INPUT FROM FILE ***
C     FILE WAS MADE AFTER INPUTTING DATA FROM SCREEN AT LEAST ONCE
C         CART 1
```

```
      READ(1,18)STA
      READ(1,16)DCA
      READ(1,16)CALI
      READ(1,16)TOSC
      READ(1,16)MOT1
      READ(1,16)CCD
      READ(1,16)NESV
      READ(1,16)CE
      READ(1,16)LIG
      READ(1,16)LE1
C                         CART 2
      READ(1,18)MOT2
      READ(1,16)FCS
      READ(1,16)LE2
C                         CART 3
      READ(1,18)LE3
   16 FORMAT(/,F12.3)
   17 FORMAT(//,F12.3)
   18 FORMAT(///,F12.3)
      ENDIF
C
C
C        *** CALCULATE POWER       ***
C
C     CART 1
         POWER1 = STA + DCA + CALI + MOT1 + CCD + NESV + CE + LIG
C                       ASSUME A POWER LOSS OF 10%
         LPOWER1 = .1*POWER1
         TPOWER1 = POWER1 + LPOWER1 + LE1
C     CART 2
         POWER2 =  MOT2 + FCS
         LPOWER2 = .1*POWER2
         TPOWER2 = POWER2 + LPOWER2 + LE3
C     CART3
         POWER3 = 0.
         LPOWER3 = .1*POWER3
         TPOWER3 = POWER3 + LPOWER3 + LE3
C
         TPOWER = TPOWER1 + TPOWER2 + TPOWER3
C
C     THE FUEL CELLS HAVE AN EFFICIENCY OF 70%. THEREFORE, THE TOTAL
C     POWER NEEDED WILL BE TPOWER/.70.
C
        EPOWER = TPOWER*((1./.70)-1.)
C
C     5% ERROR IS ADDED TO THE TOTAL POWER TO ACCOUNT FOR CHANGES LATER
C     IN THE FUTURE. THIS WILL HOPEFULLY PREVENT RESPECIFYING THE
C     ENTIRE FUEL CELL SYSTEM.
C
        ERROR = (TPOWER + EPOWER)*.05
```

```
C
C     THE TOTAL POWER WILL KNOW BE THE ADDITION OF THE PREVIOUS TOTAL
C     POWER, THE EPOWER, AND THE ERROR
C
        TPOWER = TPOWER + EPOWER + ERROR
C
C
C *** OUTPUT DATA ***
C
      WRITE(4,7) 'REQUIRED POWER FOR LUNAR ROVING VEHICLE'
      WRITE(4,14)'DESCRIPTION','POWER'
      WRITE(4,8) 'CART 1'
      WRITE(4,9) 'STEERING ASSEMBLY',STA
      WRITE(4,9) 'DRIVE CONTROL ASSEMBLY',DCA
      WRITE(4,9) 'CAMARA AND LIGHTS',CALI
      WRITE(4,9) 'MOTORS',MOT1
      WRITE(4,9) 'COMPUTER AND CONTROL DISPLAY',CCD
      WRITE(4,9) 'NAVIGATION EQUIPMENT/STEREO VISION',NESV
      WRITE(4,10) 'COMMUNICATION EQUIPMENT'
      WRITE(4,9) '    AND CONTROL ELECTRONICS',CE
      WRITE(4,9) ' DIRECTIONAL LIGHTING WITH HARDWARE',LIG
      WRITE(4,11) 'POWER',POWER1
      WRITE(4,12) '10% POWER LOSS',LPOWER1
      WRITE(4,12) 'LOCOMOTION ENERGY',LE1
      WRITE(4,12) 'TOTAL POWER',TPOWER1
      WRITE(4,8) 'CART 2'
      WRITE(4,9) 'FUEL CELL SYSTEM',FCS
      WRITE(4,9) 'MOTORS',MOT2
      WRITE(4,11) 'POWER',POWER2
      WRITE(4,12) '10% POWER LOSS',LPOWER2
      WRITE(4,12) 'LOCOMOTION ENERGY',LE2
      WRITE(4,12) 'TOTAL POWER',TPOWER2
      WRITE(4,8) 'CART 3'
      WRITE(4,11) 'POWER',POWER3
      WRITE(4,12) '10% POWER LOSS',LPOWER3
      WRITE(4,12) 'LOCOMOTION ENERGY',LE3
      WRITE(4,12) 'TOTAL POWER',TPOWER3
      WRITE(4,21) 'POWER ADDED DUE TO 70% EFFICIENT FCS',EPOWER
      WRITE(4,22) 'POWER ADDED DUE TO ERROR',ERROR
      WRITE(4,13) 'TOTAL POWER FOR LUNAR ROVING VEHICLE',TPOWER
    7 FORMAT (//,11X,A)
    8 FORMAT (//,7X,A)
    9 FORMAT (3X,A,T45,F7.2,' W')
   10 FORMAT (3X,A)
   11 FORMAT (/,6X,A,T45,F7.2,' W')
   12 FORMAT (6X,A,T45,F7.2,' W')
   13 FORMAT (5X,A,T45,F7.2,' W',///)
   14 FORMAT (///,8X,A,T48,A)
   21 FORMAT (//,5X,A,T45,F7.2,' W')
   22 FORMAT (5X,A,T45,F7.2,' W')
```

```
      PRINT '(//,A,//)', ' OUTPUT WILL BE IN POWER.OUT'
C
      WRITE(4,*) ' THE TOOLS AND SCIENTIFIC EQUIPMENT REQUIRE A POWER'
      WRITE(4,20)' OF ',TOSC,' W BUT WILL NOT BE USED AS THE VEHICLE IS'
   20 FORMAT (1X,A,F7.2,A)
      WRITE(4,*) ' MOVING.'
      STOP
      END
```

Listed below is the total power program output

```


          REQUIRED POWER FOR LUNAR ROVING VEHICLE



       DESCRIPTION                               POWER


      CART 1
  STEERING ASSEMBLY                           12.50 W
  DRIVE CONTROL ASSEMBLY                      12.50 W
  CAMARA AND LIGHTS                           16.66 W
  MOTORS                                      16.60 W
  COMPUTER AND CONTROL DISPLAY                16.50 W
  NAVIGATION EQUIPMENT/STEREO VISION          18.00 W
  COMMUNICATION EQUIPMENT
     AND CONTROL ELECTRONICS                 140.00 W
   DIRECTIONAL LIGHTING WITH HARDWARE        200.00 W

     POWER                                   432.76 W
     10% POWER LOSS                           43.28 W
     LOCOMOTION ENERGY                       514.00 W
     TOTAL POWER                             990.04 W


      CART 2
  FUEL CELL SYSTEM                           360.00 W
  MOTORS                                      16.60 W

     POWER                                   376.60 W
     10% POWER LOSS                           37.66 W
     LOCOMOTION ENERGY                       364.00 W
     TOTAL POWER                            1044.26 W


      CART 3

     POWER                                     0.00 W
```

```
      10% POWER LOSS                              0.00 W
      LOCOMOTION ENERGY                         630.00 W
      TOTAL POWER                               630.00 W


     POWER ADDED DUE TO 70% EFFICIENT FCS     1141.84 W
     POWER ADDED DUE TO ERROR                  190.31 W
     TOTAL POWER FOR LUNAR ROVING VEHICLE     3996.44 W



 THE TOOLS AND SCIENTIFIC EQUIPMENT REQUIRE A POWER
 OF 1500.00 W BUT WILL NOT BE USED AS THE VEHICLE IS
 MOVING.
```

B.2 Battery Calculations

If batteries were used as the power system of choice, only three types of batteries could be chosen based upon their high specific density and current technology.

1.) Ni-Cd. This has a specific density of 28 watthours(whr) per kilogram (kg). The efficiency of this battery is 80 %.

2.) Ni-H_2. This has a specific density of 50 whr/kg. The efficiency of this battery is 82 %.

3.) Na-S. This has a specific density of 120 whr/kg. The efficiency of this battery is 85 %.

Setting the constraints to an EVA time duration of 10 hours and a power requirement of 5.955 kW the following requirements for battery masses are:

Ni-Cd $= \frac{1kg}{25whr} * 10hrs * 5.955kW * \frac{1}{.8} = 2,658kg$

Ni-H_2 $= \frac{1kg}{50whr} * 10hrs * 5.955kW * \frac{1}{.82} = 1,191kg$

Na-S $= \frac{1kg}{120whr} * 10hrs * 5.955kW * \frac{1}{.85} = 583kg$

The above masses represent the masses of the batteries only. These masses do not include any back-up systems or heat rejection systems. At this point it was determined that fuel cells would provide a more efficient power system at a smaller mass for the Lunar ARTS.

B.3 Fuel Cells

B.3.1 Program and Output - Tank Sizing

The program listed below calculates the tank mass and tank size.

```
c This is a program to calculate the energy needed,
c   the reactant masses, empty tank mass, volume of
c          reactants and tank diameters of the Lunar ARTS fuel cells.
c
c        The LOH and LOX tanks consist of a spherical aluminum inner
c          pressure vessel, a concentric aluminum outer shell with 30
c          layers (70 layers/in) of multilayer insulation, and two vapor cooled
c          shields place between the inner and outer spheres. Reactant water
c          is stored in the the gaseous state in tanks made of a filament
c          wound Kevlar 49/epoxy matrix.
c
c Data will be assumed to be outputed to a data file
c   The data file will be named "size.out"
c
c Program written by: Melissa Van Dyke and Claudine Diaz
c Last modified: January 23, 1990.
c*******************************************************************
c Variables
c power=calculated power needed for vehicle
c time=amount of time vehicle is operating
c energy=amount of energy needed for vehicle
c LOHm=mass of liquid hydrogen
c LOXm=mass of liquid oxygen
c H2Om=mass of water produced by fuel cell
c LOHvol=volume of liquid hydrogen
c LOXvol=volume of liquid oxygen
c H2Ovol=volume of water
c        LOHd1=inner diameter of inner pressure vessel (liquid hydrogen)
c        LOHd2=outer diameter of inner pressure vessel (liquid hydrogen)
c        LOHd3=inner diameter of outer vessel (liquid hydrogen)
c        LOHd4=outer diameter of outer vessel (liquid hydrogen)
c        LOXd1=inner diameter of inner pressure vessel (liquid oxygen)
c        LOXd2=outer diameter of inner pressure vessel (liquid oxygen)
c        LOXd3=inner diameter of outer vessel (liquid oxygen)
c        LOXd4=outer diameter of outer vessel (liquid oxygen)
c        H2Od1=inner diameter of water storage tank
c        H2Od2=outer diameter of water storage tank
c        TOHinn=inner pressure vessel thickness (liquid hydrogen)
c        TOHins=insulation thickness (liquid hydrogen)
c        TOHout=outer vessel thickness (liquid hydrogen)
c        TOXinn=inner pressure vessel thickness (liquid oxygen)
c        TOXins=insulation thickness (liquid oxygen)
c        TOXout=outer vessel thickness (liquid oxygen)
c        TH2O=thickness of water storage tank
c        UTSIAL=yield strength of Aluminum 2219-T6
c        UTSOAl=yield strength of Aluminum 6061-T6
c        UTSKEV=yield strength of Kevlar 49/epoxy matrix
```

```
c        DENIAL=density of Aluminum 2219-T6
c        DENOAL=density of Aluminum 6061-T6
c        DENKEV=density of Kevalr 49/epoxy matrix
c        DENINS=density of the 90 layer insulation
c        N=factor of safety
c        POH=pressure liquid hydrogen is stored in tank
c        POX=pressure liquid oxygen is stored in tank
c        PH2O=pressure water is stored in tank
c        HTANKM=mass of empty liquid hydrogen tank
c        OTANKM=mass of empty liquid oxygen tank
c        WTANKM=mass of empty water tank
c*****************************************************************
Real power,time,energy,N,Vol,Mass,lohm,loxm,h2om
Real     lohvol,loxvol,h2ovol,lohd1,loxd1,h2od1
         Real     lohd2,loxd2,h2od2,lohd3,loxd3,lohd4,loxd4
         Real     tohinn,tohins,tohout,toxinn,toxins,toxout
         Real     th2o,UTSIAL,UTSOAL,UTSKEV
         Real     DENIAL,DENOAL,DENKEV,DENINS,POH,POX,PH2O
         Real     HTANKM,OTANKM,WTANKM
c
open (1,file='size.out',status='new',carriage control='list')
c
c        Give values to constants in metric.
c        The yield strengths and the pressure are in Pa.
c        The densities are in kg/m*m*m.
c        The thickness of the insulation based on 70 layers/in
c        is in meters.
c
         UTSIAL=75.8e6
         UTSOAL=275.8e6
         UTSKEV=233e6
         DENIAL=2795.7
         DENOAL=2712.6
         DENKEV=1356.3
         DENINS=320.4
         N=1.3
         POH=20.7e6
         POX=20.7e6
         PH2O=2.2e6
         tohins=.023
         toxins=.023
c
print *,'Input the amount of power required in Kilowatts'
read (*,*)power
print *,'Input the time duration of the mission in hours'
read (*,*)time

c  Calculate the energy required and send to output file
energy=power*time
write(1,10)energy
```

```
 10 format ('The energy required is Kilowatt Hours',f9.5)

c  Calculate the reactant mass and send to output file.
c  The consumption rate of the liquid hydrogen is .04 kg/kWhr. The
c  consumption rate of the liquid oxygen is .32 kg/kWhr. THe production
c  rate of the water is .36 kg/kWhr.
c  The mass of the reactants is increased by 5% to account for
c  reactant residual. The water is also increased by 5% because of
c  initial water needed in tank.
 lohm=.04*energy*1.05
 loxm=.32*energy*1.05
 h2om=.36*energy*1.1
 write (1,5)
 5 format (/,'Calculation of reactant masses')
 write(1,20)lohm,lohm*2.205
 20 format ('The mass of liquid hydrogen needed is ',f9.5,' kg'
     a  ,'  (',f9.5,' lbf)')
 write (1,30)loxm,loxm*2.205
 30 format('The mass of liquid oxygen needed is ',f9.5,' kg'
     a  ,'  (',f9.5,' lbf)')
 write (1,40)h2om,loxm*2.205
 40 format('The mass of water produced is ',f9.5,' kg'
     a  ,'  (',f9.5,' lbf)')
c
c  Calculation of reactant volumes. The density of liquid hydrogen is
c  67.2 kg/m*m*m. The density of liquid oxygen is 1121.6 kg/m*m*m. The
c  density of water is 999.55 kg/m*m*m.
 lohvol=lohm/67.2
 loxvol=loxm/1121.6
 h2ovol=h2om/999.55
 write (1,60)
 60 format(/,'Calculation of reactant volumes')
 write(1,70)lohvol,lohvol*35.32
 70 format('The volume of liquid hydrogen is ',f7.5,' m*m*m'
     a   ,'  (',f7.5,' ft*ft*ft)')
 write (1,80)loxvol,loxvol*35.32
 80 format('The volume of liquid oxygen is ',f7.5,' m*m*m'
     a   ,'  (',f7.5,' ft*ft*ft)')
 write (1,100)h2ovol,h2ovol*35.32
 100 format('The volume of water is ',f7.5,' m*m*m'
     a   ,'  (',f7.5,' ft*ft*ft)')
c
c  Calculation of Tank diameters
c  The volume is increased by 10% to account for maximum filling.
 lohd1=(.0298*lohvol*1.1)**(1./3.)
 loxd1=(.0298*loxvol*1.1)**(1./3.)
 h2od1=(.0298*h2ovol*1.1)**(1./3.)
c
c  Calculate the dimensions of the hydrogen tank
c  Assume the pressure that the reactant is stored is
```

```
c  the pressure that is exerted on the walls of both the inner
c  and outer vessel.
c
c  Initially calculate the thickness of the inner pressure vessel
c  using the pressure the reactant is stored and the ultimate tensile
c  strength of the material of the inner pressure vessel (Aluminum 2219).
c  Add the thickness to the inner diameter which was calculated earlier
c  in the program. Using the inner and outer diameter, the volume and
c  mass of the inner vessel can be calculated.
c
c  Inner Pressure vessel
      tohinn = (POH*N*(lohd1/2))/(2*UTSIAL)
      lohd2 = lohd1 + 2*lohinn
      Vol = .1667*3.14*(lohd2**3 - lohd1**3)
      HTANKM = Vol * DENIAL
c
c
c  Using the thickness of the insulation, determine the volume and mass
c  of the insulation.
c
c  Insulation
      lohd3 = lohd2 + 2*tohins
      Vol = .1667*3.14*(lohd3**3 - lohd2**3)
      Mass = DENINS * Vol
      HTANKM = HTANKM + Mass
c
c  Add the thickness of the insulation to the outer diameter of the inner
c  pressure vessel to obtain the inner diameter of the outer vessel. Using
c  the pressure inside the inner pressure vessel and the ultimate tensile
c  strength of the material the outer vessel is made of (Aluminum 6061),
c  the thickness of the outer vessel can be determined. Once the thickness
c  is known, the volume and mass of the outer vessel can be determined.
c  Adding the mass of the inner vessel, insulation, and outer vessel, the
c  mass of the empty tank can be determined.
c
c  Outer Vessel
      tohout = (POH*N*(lohd3/2))/(2*UTSOAL)
      lohd4 = lohd3 + 2*tohout
      Vol = 1.667*3.14*(lohd4**3 - lohd3**3)
      Mass = DENOAL * Vol
      HTANKM = HTANKM + Mass
c
c  Output to file
      write(1,160)
 160  format(////,'Liquid Hydrogen Tank')
      write(1,170)lohd1,lohd1/.0254
 170  format(/,'The inner diameter of the inner vessel is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,180)tohinn, tohinn/.0254
 180  format('The thickness of the inner vessel is ',f7.5,' m'
```

```
     a,'  (',f7.5,' in)')
      write(1,190)tohins,tohins/.0254
 190  format('The thickness of the insulation is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,200)lohd3,lohd3/.0254
 200  format('The inner diameter of the outer vessel is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,210)tohout,tohout/.0254
 210  format('The thickness of the outer vessel is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,220)lohd4,lohd4/.0254
 220  format(/,'The outer diameter of the hydrogen tank is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,230)HTANKM, HTANKM *2.205
 230  format('The empty tank mass is ',f9.5,' kg'
     a,'  (',f9.5,'  lbf)')
c
c
c  Calculate the dimensions of the oxygen tank
c  Assume the pressure that the reactant is stored in is
c  the pressure that is exerted on the walls of the inner
c  and outer vessel.
c
c  The process of determining the parameters of the hydrogen tank is
c  the same procedure for the oxygen tank.
c
c  Inner Pressure vessel
      toxinn = (POX*N*(loxd1/2))/(2*UTSIAL)
      loxd2 = loxd1 + 2*loxinn
      Vol = .1667*3.14*(loxd2**3 - loxd1**3)
      OTANKM = Vol * DENIAL
c
c  Insulation
      loxd3 = loxd2 + 2*toxins
      Vol = .1667*3.14*(loxd3**3 - loxd2**3)
      Mass = DENINS * Vol
      OTANKM = OTANKM + Mass
c
c  Outer Vessel
      toxout = (POX*N*(loxd3/2))/(2*UTSOAL)
      loxd4 = loxd3 + 2*toxout
      Vol = 1.667*3.14*(loxd4**3 - loxd3**3)
      Mass = DENOAL * Vol
      OTANKM = OTANKM + Mass
c
c  Output to file
      write(1,165)
 165  format(///'Liquid Oxygen Tank')
      write(1,170)loxd1,loxd1/.0254
      write(1,180)toxinn,toxinn/.0254
```

```
      write(1,190)toxins,toxins/.0254
      write(1,200)loxd3,loxd3/.0254
      write(1,210)toxout,toxout/.0254
      write (1,225)loxd4,loxd4/.0254
 225  format(/,'The outer diameter of the oxygen tank is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,230)OTANKM,OTANKM*2.205
c
c  Calculate the dimensions of the water storage tank
c  Calculate the thickness of the tank by using the pressure under
c  which the water is stored and by using the ultimate tensile
c  strength of the material the tank is made of (Kevlar 49/epoxy matrix).
c  Adding the thickness to the inner diameter will determine the outer
c  diameter and then the mass and volume of the empty tank can be
c  determined.
c
      th2o = (PH2O*N*(h2od1/2))/(2*UTSKEV)
      h2od2 = h2od1 + 2*th2o
      Vol = .1667*3.14*(h2od2**3 - h2od1**3)
      WTANKM = Vol * DENKEV
c
c  Output to file
      write(1,240)
 240  format(///,'Water Storage Tank')
      write(1,250)h2od1,h2od1/.0254
 250  format(/,'The inner diameter of the tank is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,260)th2o,th2o/.0254
 260  format('The thickness of the tank is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,270)h2od2,h2od2/.0254
 270  format(/,'The outer diameter of the water tank is ',f7.5,' m'
     a,'  (',f7.5,' in)')
      write(1,280)WTANKM,WTANKM*2.205
 280  format('The mass of the empty tank is ',f9.5,' kg'
     a,'  (',f9.5,' lbf)')
c
 stop
 end
```

Listed below is the output of the tank sizing program. The input for the program is by keyboard. The required entries are duration of travel in hours and total power required in kW. The data output is to a file and returns reactant mass and volume, the dimensions and mass of the hydrogen, oxygen, and water tank.

```
The energy required is Kilowatt Hours 60.00000

Calculation of reactant masses
The mass of liquid hydrogen needed is   2.52000 kg  (  5.55660 lbf)
The mass of liquid oxygen needed is  20.16000 kg  ( 44.45279 lbf)
The mass of water produced is  23.76000 kg  ( 44.45279 lbf)
```

```
Calculation of reactant volumes
The volume of liquid hydrogen is 0.03750 m*m*m  (1.32450 ft*ft*ft)
The volume of liquid oxygen is 0.01797 m*m*m  (0.63485 ft*ft*ft)
The volume of water is 0.02377 m*m*m  (0.83958 ft*ft*ft)




Liquid Hydrogen Tank

The inner diameter of the inner vessel is 0.10712 m  (4.21741 in)
The thickness of the inner vessel is 0.00951 m  (0.37431 in)
The thickness of the insulation is 0.02300 m  (0.90551 in)
The inner diameter of the outer vessel is 0.15312 m  (6.02844 in)
The thickness of the outer vessel is 0.00374 m  (0.14705 in)

The outer diameter of the hydrogen tank is 0.16059 m  (6.32254 in)
The empty tank mass is   8.22651 kg  ( 18.13944  lbf)



Liquid Oxygen Tank

The inner diameter of the inner vessel is 0.08383 m  (3.30055 in)
The thickness of the inner vessel is 0.00744 m  (0.29293 in)
The thickness of the insulation is 0.02300 m  (0.90551 in)
The inner diameter of the outer vessel is 0.12983 m  (5.11158 in)
The thickness of the outer vessel is 0.00317 m  (0.12469 in)

The outer diameter of the oxygen tank is 0.13617 m  (5.36095 in)
The empty tank mass is   5.04181 kg  ( 11.11718  lbf)



Water Storage Tank

The inner diameter of the tank is 0.09202 m  (3.62285 in)
The thickness of the tank is 0.00028 m  (0.01112 in)

The outer diameter of the water tank is 0.09259 m  (3.64508 in)
The mass of the empty tank is   0.01025 kg  (  0.02260 lbf)
```

B.3.2 Stack Sizing

The stacks have to be sized to the parameters of the system. The fuel cell stack has a specific mass of 9.0 lb/kW (4.081 kg/kW) and and a specific volume of .25 ft^3 as stated in the stack section.

For this system:

$Mass = 4.081 kg/kW * 5.955 kW = 24.3026 kg$

$Volume = .15 ft^3/kW * 5.955 kW = .893 ft^3$

Each cell is approximately 1 ft^2.

The radius of each cell:

$\pi r^2 = 1\ ft^2$

r = .564 ft (.172 m)

C.1 Stress Calculations

A manual analysis of some beams was performed to verify results from the finite element analysis. The vertical mounting beam for the suspension system was chosen for analysis because it is subjected to side forces from the lower control arm and mounting of the shock absorber, as well as thermal loads. The left and right side of the lunar vehicle are assumed to be symmetric about the center of the cart along the z-axis, therefore, the stress calculations were performed for only one side of the vehicle. Relevant formulas and identites are as follows:

$$\sigma = \frac{P}{A} - \frac{M_z y}{I_{zz}} + \frac{M_y z}{I_{yy}} + E\alpha\Delta T$$
$$\epsilon = \frac{P}{EA} - \frac{M_z y}{EI_{zz}} + \frac{M_y z}{EI_{yy}}$$
$$I_{yy} = I_{yy'} + z_i^2 A_i$$
$$I_{zz} = I_{zz'} + y_i^2 A_i$$
$$I_{yz} = I_{yz'} + y_i z_i A_i$$
$$g_m = 5.37 \text{ ft/ sec}^2$$

The results of this analysis showed that the stresses verified the results produced by the finite element analysis.

C.2 Finite Element

C.2.1 Finite Element - Chassis Description (Second Cart)

```
C *** TITLE MSC/PAL2   LUNAR ROVER VEHICLE
C *** DEFINE NODAL POINTS
NODAL POINT LOCATIONS 1
1  6, 0, 0
2  7, 0, 0,
3  6, 4.5, 0
4  11, 0, 0
5  12, 0, 0
6  12, 4.5 0
7  6, 0, 3
8  7, 0, 3
9  6, 4.5, 3
10 11, 0, 3
11 12, 0, 3
12 12, 4.5, 3
13 6, 0, 6
14 7, 0, 6
15 11, 0, 6
16 12, 0, 6
17 6, 0, 9
18 7, 0, 9
19 6, 4.5, 9
20 11, 0, 9
21 12, 0, 9
22 12, 4.5, 9
```

```
23 6, 3, 3
24 6, 3, 6
25 6, 4.5, 6
26 5, 4.5, 4.5
27 6, 3, 4.5
28 12, 3, 3
29 12, 3, 6
30 12, 4.5, 6
31 13, 4.5, 4.5
32 12, 3, 4.5
33 9, 0, 0
34 9, 0, 3
35 9, 0, 6
36 9, 0, 9

C *** DEFINE ALUMINUM MATERIAL PROPERTIES
C YOUNG'S MODULUS, SHEAR MODULUS, MASS DENSITY, POISSON'S RATIO.
C TENSILE YIELD STRENGTH (ALL ON ONE LINE)
MATERIAL PROPERTIES 10.6E6, 3.9E6, .101, .26, 60E3
BEAM TYPE 1, 0.484, .2, 0.19, 0.19
CONNECT 1 TO 3
CONNECT 2 TO 3
CONNECT 4 TO 6
CONNECT 5 TO 6
CONNECT 3 TO 6
CONNECT 3 TO 9
CONNECT 6 TO 12
CONNECT 11 TO 28
CONNECT 10 TO 28
CONNECT 28 TO 12
CONNECT 8 TO 23
CONNECT 7 TO 23
CONNECT 23 TO 9
CONNECT 9 TO 26
CONNECT 9 TO 25
CONNECT 26 TO 25
CONNECT 23 TO 27
CONNECT 27 TO 24
CONNECT 27 TO 26
CONNECT 12 TO 31
CONNECT 31 TO 30
CONNECT 12 TO 30
CONNECT 28 TO 32
CONNECT 32 TO 29
CONNECT 31 TO 32
CONNECT 16 TO 29
CONNECT 15 TO 29
CONNECT 29 TO 30
CONNECT 14 TO 24
CONNECT 13 TO 24
```

```
CONNECT 24 TO 25
CONNECT 25 TO 19
CONNECT 30 TO 22
CONNECT 21 TO 22
CONNECT 20 TO 22
CONNECT 18 TO 19
CONNECT 17 TO 19
CONNECT 19 TO 22
QUAD 1 0 .1 0.0
CONNECT 1 TO 7 TO 8 TO 2
CONNECT 2 TO 33 TO 34 TO 8
CONNECT 33 TO 34 TO 10 TO 4
CONNECT 4 TO 10 TO 11 TO 5
CONNECT 11 TO 16 TO 15 TO 10
CONNECT 10 TO 15 TO 35 TO 34
CONNECT 34 TO 35 TO 14 TO 8
CONNECT 8 TO 7 TO 13 TO 14
CONNECT 13 TO 14 TO 18 TO 17
CONNECT 14 TO 18 TO 36 TO 35
CONNECT 35 TO 36 TO 20 TO 15
CONNECT 15 TO 16 TO 21 TO 20

C *** DEFINE BOUNDARY CONDITIONS
C *** SET ALL ROTATIONS EQUAL TO ZERO
ZERO 1
RA OF 26 27 31 32
TX OF 1 2 4 5 7 8 10 11 13 14 15 16 17 18 20 21 33 34 35 36
TZ OF 1 2 4 5 7 8 10 11 13 14 15 16 17 18 20 21 33 34 35 36
TA OF 27 32

END DEFINITION
```

C.2.2 Finite Element - Load Description

```
FORCES AND MOMENTS APPLIED 1
FY 287.3 26 31
FX 430.6 26
FX -430.6 31
FY 200 23 24
FY 200 28 29
FX 100 23 24
FX -100 28 29

SOLVE
QUIT
```

C.2.3 Finite Element - Results

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MSC/PAL2 -- LUNAR ROVER VEHICLE

STATIC ANALYSIS SUBCASE NO. 1 APPLIED FORCES

NODE	DIR	VALUE	NODE	DIR	VALUE	NODE	DIR	VALUE
23	X T	1.000E+02	23	Y T	2.000E+02	24	X T	1.000E+02
24	Y T	2.000E+02	26	X T	4.306E+02	26	Y T	2.873E+02
28	X T	-1.000E+02	28	Y T	2.000E+02	29	X T	-1.000E+02
29	Y T	2.000E+02	31	X T	-4.306E+02	31	Y T	2.873E+02

STATIC ANALYSIS SUBCASE NO. 1 EXTERNAL FORCES

NODE	DIR	VALUE	NODE	DIR	VALUE	NODE	DIR	VALUE

STATIC ANALYSIS SUBCASE NO. 1 DISPLACEMENTS

NODE	X TRANS	Y TRANS	Z TRANS	X ROT	Y ROT	Z ROT
3	5.7765E-04	7.3181E-05	-3.4513E-03	0.0000E-01	0.0000E-01	0.0000E-01
6	-5.7765E-04	7.3181E-05	-3.4513E-03	0.0000E-01	0.0000E-01	0.0000E-01
9	1.2216E+00	3.0462E-02	-3.4516E-03	0.0000E-01	0.0000E-01	0.0000E-01
12	-1.2216E+00	3.0462E-02	-3.4516E-03	0.0000E-01	0.0000E-01	0.0000E-01
19	5.7765E-04	7.3181E-05	3.4513E-03	0.0000E-01	0.0000E-01	0.0000E-01
22	-5.7765E-04	7.3181E-05	3.4513E-03	0.0000E-01	0.0000E-01	0.0000E-01
23	1.6229E-01	2.9401E-02	-6.6047E-06	0.0000E-01	0.0000E-01	0.0000E-01
24	1.6229E-01	2.9401E-02	6.6047E-06	0.0000E-01	0.0000E-01	0.0000E-01
27	3.1233E-01	3.8094E-01	-5.0926E-14	0.0000E-01	0.0000E-01	0.0000E-01
28	-1.6229E-01	2.9401E-02	-6.6047E-06	0.0000E-01	0.0000E-01	0.0000E-01
29	-1.6229E-01	2.9401E-02	6.6047E-06	0.0000E-01	0.0000E-01	0.0000E-01
30	-1.2216E+00	3.0462E-02	3.4516E-03	0.0000E-01	0.0000E-01	0.0000E-01
31	-1.2358E+00	9.9774E-01	1.4896E-13	0.0000E-01	0.0000E-01	0.0000E-01
32	-3.1233E-01	3.8094E-01	1.4015E-13	0.0000E-01	0.0000E-01	0.0000E-01

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STATIC ANALYSIS SUBCASE NO. 1 ELEMENT RECOVERY

	MAXIMUM STRESSES FOR BEAM			VON MISES CRITERION				
ELEMENT	MAJOR	MINOR	SHEAR	STRESS	% YIELD	@NODE	CONNECTIVITY	
8	8.657E+03	0.000E-01	4.329E+03	8.657E+03	14.4	28	11	28
9	7.683E-14	-6.544E+03	3.272E+03	6.544E+03	10.9	28	10	28
11	8.682E-14	-6.544E+03	3.272E+03	6.544E+03	10.9	23	8	23
12	8.657E+03	0.000E-01	4.329E+03	8.657E+03	14.4	7	7	23
14	4.441E-14	-2.454E+03	1.227E+03	2.454E+03	4.1	26	9	26
15	2.033E+03	0.000E-01	1.016E+03	2.033E+03	3.4	25	9	25
16	1.554E-14	-2.454E+03	1.227E+03	2.454E+03	4.1	25	26	25
20	2.998E-14	-2.454E+03	1.227E+03	2.454E+03	4.1	31	12	31
21	4.441E-14	-2.454E+03	1.227E+03	2.454E+03	4.1	30	31	30

22	2.033E+03	0.000E-01	1.016E+03	2.033E+03	3.4	30	12	30
26	8.657E+03	0.000E-01	4.329E+03	8.657E+03	14.4	16	16	29
27	-7.350E-14	-6.544E+03	3.272E+03	6.544E+03	10.9	15	15	29
29	-5.684E-14	-6.544E+03	3.272E+03	6.544E+03	10.9	14	14	24
26	8.657E+03	0.000E-01	4.329E+03	8.657E+03	14.4	24	13	24

C.2.4 Finite Element - Geometric Optimization

Listed below is a FORTRAN file which calculates the inertia properties of an L-beam. This was used in the optimization of the sizes. The inputted thickness and side length are standardized.

```
* this program calculates the inertia properties of L-beams
       REAL INERTIA,I1,I2,LENGTH

100    CONTINUE
       PRINT*,'  '
       PRINT*,'  '
       PRINT*,'Enter side length of L-BEAM'
       READ*, LENGTH
       PRINT*,'Enter thickness of L_BEAM'
       READ*,THICK

* calculate centroid
       Y1=LENGTH/2.
       A1=LENGTH*THICK
       Y2=THICK/2.
       A2=(LENGTH-THICK)*THICK

       ELEM1=Y1*A1
       ELEM2=Y2*A2
       SUM=ELEM1+ELEM2

       CENTROID=SUM/(A1+A2)

* calculate inertias
       I1=((LENGTH-THICK)*THICK**3)/12.+
     $      A2*(CENTROID-Y2)**2
       I2=(THICK*LENGTH**3)/12.+A1*(CENTROID-Y1)**2

       INERTIA=I1+I2

* print out results
       PRINT*,'  '
       PRINT*,'The inertia is ', INERTIA
       PRINT*,'The cross sectional area is ', A1+A2
       PRINT*,'The polar inertia is ,',INERTIA*2.
       PRINT*,'  '

*prompt user for another try
```

```
      PRINT*,'Do you want to do another?  1 -> Yes    2 -> No'
      READ*,N
      IF(N.EQ.1)GOTO 100

      END
```

C.3 DADS Analysis - Loading File

```

ANALYSIS
CREATE SYSTEM.DATA
   UNITS                               := 'ENGLISH'
   ANALYSIS.TYPE                       := 'DYNAMIC'
   STARTING.TIME                       := '0.0'
   ENDING.TIME                         := '5.0'
   PRINT.INTERVAL                      := '.1'
   GRAVITY.SEA.LEVEL                   := '32.174'
   X.GRAVITY                           := '0.0'
   Y.GRAVITY                           := '-1.0'
   SCALE.GRAVITY.COEF                  := '.1667'
   MATRIX.OPERATIONS                   := 'SPARSE'
   REDUNDANCY.CHECK                    := 'TRUE'
   LU.TOL                              := '1.0D-12'
   ASSEMBLY.TOL                        := '1.0D-3'
   BYPASS.ASSEMBLY                     := 'TRUE'
   OUTPUT.FILE                         := 'BOTH'
   REFERENCE.FRAME                     := 'LOCAL'
   DEBUG.FLAG                          := 'FALSE'
UP
CREATE DYNAMIC.DATA
   REACTION.FORCES                     := 'TRUE'
   FORCE.COORDINATES                   := 'GLOBAL'
   PRINT.METHOD                        := 'INTERPOLATED'
   MAX.INT.STEP                        := '.1'
   SOLUTION.TOL                        := '0.001'
   INTEGRATION.TOL                     := '0.0001'
UP
UP
FORCE
CREATE TSDA
   NAME                                := 'TSDA1'
   BODY.1.NAME                         := 'DAMPER'
   BODY.2.NAME                         := 'PLUNGER'
   SPRING.CONSTANT                     := '1100.0'
   FREE.LENGTH.SPRING                  := '1.1'
   DAMPING.COEFFICIENT                 := '142.0'
   ACTUATOR.FORCE                      := '0.0'
   P.ON.BODY.1                         := ( -.375, 0.0 )
   P.ON.BODY.2                         := ( .375, 0.0 )
```

```
    Q.ON.BODY.1                 := ( 1.375, 0.0 )
    Q.ON.BODY.2                 := ( 1.375, 0.0 )
    CURVE.SPRING                := 'NONE'
    CURVE.DAMPER                := 'NONE'
    CURVE.ACTUATOR              := 'NONE'
    NODE.1                      := '0'
    NODE.2                      := '0'
UP
CREATE TSDA
    NAME                        := 'TSDA2'
    BODY.1.NAME                 := 'PLUNGER2'
    BODY.2.NAME                 := 'DAMPER2'
    SPRING.CONSTANT             := '0.0'
    FREE.LENGTH.SPRING          := '0.0'
    DAMPING.COEFFICIENT         := '0.0'
    ACTUATOR.FORCE              := '0.0'
    P.ON.BODY.1                 := ( .75, 0.0 )
    P.ON.BODY.2                 := ( -.75, 0.0 )
    Q.ON.BODY.1                 := ( 1.75, 0.0 )
    Q.ON.BODY.2                 := ( 1.75, 0.0 )
    CURVE.SPRING                := 'NONE'
    CURVE.DAMPER                := 'NONE'
    CURVE.ACTUATOR              := 'CURVE1'
    NODE.1                      := '0'
    NODE.2                      := '0'
UP
UP
JOINTS
CREATE REVOLUTE.JOINT
    NAME                        := 'REV1'
    BODY.1.NAME                 := 'GROUND'
    BODY.2.NAME                 := 'FOLLOWER1'
    P.ON.BODY.1                 := ( 0.0, 0.0 )
    P.ON.BODY.2                 := ( -1.96, 0.0 )
    Q.ON.BODY.1                 := ( 1.0, 0.0 )
    Q.ON.BODY.2                 := ( 0.96, 0.0 )
    NODE.1                      := '0'
    NODE.2                      := '0'
UP
CREATE REVOLUTE.JOINT
    NAME                        := 'REV2'
    BODY.1.NAME                 := 'GROUND'
    BODY.2.NAME                 := 'FOLLOWER2'
    P.ON.BODY.1                 := ( 0.0, .333 )
    P.ON.BODY.2                 := ( -1.96, 0.0 )
    Q.ON.BODY.1                 := ( 1.0, .333 )
    Q.ON.BODY.2                 := ( 0.96, 0.0 )
    NODE.1                      := '0'
    NODE.2                      := '0'
UP
```

```
CREATE REVOLUTE.JOINT
    NAME                                   := 'REV3'
    BODY.1.NAME                            := 'GROUND'
    BODY.2.NAME                            := 'DAMPER'
    P.ON.BODY.1                            := ( 0.0, 1.167 )
    P.ON.BODY.2                            := ( -.375, 0 )
    Q.ON.BODY.1                            := ( 1.0, 1.167 )
    Q.ON.BODY.2                            := ( 1.375, 0 )
    NODE.1                                 := '0'
    NODE.2                                 := '0'
UP
CREATE REVOLUTE.JOINT
    NAME                                   := 'REV4'
    BODY.1.NAME                            := 'FOLLOWER2'
    BODY.2.NAME                            := 'PLUNGER'
    P.ON.BODY.1                            := ( -1.127, 0.0 )
    P.ON.BODY.2                            := ( .375, 0.0 )
    Q.ON.BODY.1                            := ( 0.127, 0.0 )
    Q.ON.BODY.2                            := ( 1.375, 0.0 )
    NODE.1                                 := '0'
    NODE.2                                 := '0'
UP
CREATE REVOLUTE.JOINT
    NAME                                   := 'REV5'
    BODY.1.NAME                            := 'FOLLOWER2'
    BODY.2.NAME                            := 'CONNECTOR'
    P.ON.BODY.1                            := ( .04, 0.0 )
    P.ON.BODY.2                            := ( -.1665, 0.0 )
    Q.ON.BODY.1                            := ( 1.04, 0.0 )
    Q.ON.BODY.2                            := ( 1.1665, 0.0 )
    NODE.1                                 := '0'
    NODE.2                                 := '0'
UP
CREATE REVOLUTE.JOINT
    NAME                                   := 'REV6'
    BODY.1.NAME                            := 'CONNECTOR'
    BODY.2.NAME                            := 'FOLLOWER1'
    P.ON.BODY.1                            := ( .1665, 0.0 )
    P.ON.BODY.2                            := ( .04, 0.0 )
    Q.ON.BODY.1                            := ( 1.1665, 0.0 )
    Q.ON.BODY.2                            := ( 1.04, 0.0 )
    NODE.1                                 := '0'
    NODE.2                                 := '0'
UP
CREATE REVOLUTE.JOINT
    NAME                                   := 'REV7'
    BODY.1.NAME                            := 'GROUND'
    BODY.2.NAME                            := 'PLUNGER2'
    P.ON.BODY.1                            := ( 2.0, -2.0 )
    P.ON.BODY.2                            := ( -.75, 0.0 )
```

```
    Q.ON.BODY.1                     := ( 3.0, -2.0 )
    Q.ON.BODY.2                     := ( 1.75, 0.0 )
    NODE.1                          := '0'
    NODE.2                          := '0'
UP
CREATE TRANSLATIONAL.JOINT
    NAME                            := 'TRANS1'
    BODY.1.NAME                     := 'DAMPER'
    BODY.2.NAME                     := 'PLUNGER'
    P.ON.BODY.1                     := ( -.375, 0 )
    P.ON.BODY.2                     := ( .375, 0 )
    Q.ON.BODY.1                     := ( 1.375, 0 )
    Q.ON.BODY.2                     := ( 1.375, 0 )
    NODE.1                          := '0'
    NODE.2                          := '0'
UP
CREATE TRANSLATIONAL.JOINT
    NAME                            := 'TRANS2'
    BODY.1.NAME                     := 'PLUNGER2'
    BODY.2.NAME                     := 'DAMPER2'
    P.ON.BODY.1                     := ( .75, 0.0 )
    P.ON.BODY.2                     := ( -.75, 0.0 )
    Q.ON.BODY.1                     := ( 1.75, 0.0 )
    Q.ON.BODY.2                     := ( 1.75, 0.0 )
    NODE.1                          := '0'
    NODE.2                          := '0'
UP
UP
CREATE BODY
    NAME                            := 'GROUND'
    CENTER.OF.GRAVITY               := ( 0.0, 0.0 )
    PHI                             := '0.0'
    FIXED.TO.GROUND                 := 'TRUE'
    MASS                            := '1.0'
    INERTIA                         := '1.0'
    XG.FORCE                        := '0.0'
    YG.FORCE                        := '0.0'
    TORQUE.CONSTANT                 := '0.0'
    CURVE.XGF                       := 'NONE'
    CURVE.YGF                       := 'NONE'
    CURVE.TORQUE                    := 'NONE'
    OUTLINE.SHAPE                   := 'NONE'
    SHAPE.CENTER                    := ( 0.0, 0.0 )
    ANGULAR.UNITS                   := 'DEGREES'
    FLEXIBLE                        := 'FALSE'
    SUPERELEMENT                    := 'FALSE'
UP
CREATE BODY
    NAME                            := 'FOLLOWER1'
    CENTER.OF.GRAVITY               := ( 1.96, 0.0 )
```

```
    PHI                          := '0.0'
    FIXED.TO.GROUND              := 'FALSE'
    MASS                         := '.685'
    INERTIA                      := '.2283'
    XG.FORCE                     := '0.0'
    YG.FORCE                     := '0.0'
    TORQUE.CONSTANT              := '0.0'
    CURVE.XGF                    := 'NONE'
    CURVE.YGF                    := 'NONE'
    CURVE.TORQUE                 := 'NONE'
    OUTLINE.SHAPE                := 'NONE'
    SHAPE.CENTER                 := ( 0.0, 0.0 )
    ANGULAR.UNITS                := 'DEGREES'
    FLEXIBLE                     := 'FALSE'
    SUPERELEMENT                 := 'FALSE'
UP
CREATE BODY
    NAME                         := 'FOLLOWER2'
    CENTER.OF.GRAVITY            := ( 1.96, .333 )
    PHI                          := '0.0'
    FIXED.TO.GROUND              := 'FALSE'
    MASS                         := '.685'
    INERTIA                      := '.2283'
    XG.FORCE                     := '0.0'
    YG.FORCE                     := '0.0'
    TORQUE.CONSTANT              := '0.0'
    CURVE.XGF                    := 'NONE'
    CURVE.YGF                    := 'NONE'
    CURVE.TORQUE                 := 'NONE'
    OUTLINE.SHAPE                := 'NONE'
    SHAPE.CENTER                 := ( 0.0, 0.0 )
    ANGULAR.UNITS                := 'DEGREES'
    FLEXIBLE                     := 'FALSE'
    SUPERELEMENT                 := 'FALSE'
UP
CREATE BODY
    NAME                         := 'CONNECTOR'
    CENTER.OF.GRAVITY            := ( 2.0, .1665 )
    PHI                          := '90'
    FIXED.TO.GROUND              := 'FALSE'
    MASS                         := '35.113'
    INERTIA                      := '.3245'
    XG.FORCE                     := '0.0'
    YG.FORCE                     := '0.0'
    TORQUE.CONSTANT              := '0.0'
    CURVE.XGF                    := 'NONE'
    CURVE.YGF                    := 'NONE'
    CURVE.TORQUE                 := 'NONE'
    OUTLINE.SHAPE                := 'NONE'
    SHAPE.CENTER                 := ( 0.0, 0.0 )
```

```
    ANGULAR.UNITS                    := 'DEGREES'
    FLEXIBLE                         := 'FALSE'
    SUPERELEMENT                     := 'FALSE'
UP
CREATE BODY
    NAME                             := 'DAMPER'
    CENTER.OF.GRAVITY                := ( .265, .902 )
    PHI                              := '-45'
    FIXED.TO.GROUND                  := 'FALSE'
    MASS                             := '.2569'
    INERTIA                          := '.012'
    XG.FORCE                         := '0.0'
    YG.FORCE                         := '0.0'
    TORQUE.CONSTANT                  := '0.0'
    CURVE.XGF                        := 'NONE'
    CURVE.YGF                        := 'NONE'
    CURVE.TORQUE                     := 'NONE'
    OUTLINE.SHAPE                    := 'NONE'
    SHAPE.CENTER                     := ( 0.0, 0.0 )
    ANGULAR.UNITS                    := 'DEGREES'
    FLEXIBLE                         := 'FALSE'
    SUPERELEMENT                     := 'FALSE'
UP
CREATE BODY
    NAME                             := 'PLUNGER'
    CENTER.OF.GRAVITY                := ( .568, .598 )
    PHI                              := '135'
    FIXED.TO.GROUND                  := 'FALSE'
    MASS                             := '.2'
    INERTIA                          := '.00938'
    XG.FORCE                         := '0.0'
    YG.FORCE                         := '0.0'
    TORQUE.CONSTANT                  := '0.0'
    CURVE.XGF                        := 'NONE'
    CURVE.YGF                        := 'NONE'
    CURVE.TORQUE                     := 'NONE'
    OUTLINE.SHAPE                    := 'NONE'
    SHAPE.CENTER                     := ( 0.0, 0.0 )
    ANGULAR.UNITS                    := 'DEGREES'
    FLEXIBLE                         := 'FALSE'
    SUPERELEMENT                     := 'FALSE'
UP
CREATE BODY
    NAME                             := 'PLUNGER2'
    CENTER.OF.GRAVITY                := ( 2.0, -1.25 )
    PHI                              := '0.0'
    FIXED.TO.GROUND                  := 'FALSE'
    MASS                             := '1.0'
    INERTIA                          := '1.0'
    XG.FORCE                         := '0.0'
```

```
    YG.FORCE                              := '0.0'
    TORQUE.CONSTANT                       := '0.0'
    CURVE.XGF                             := 'NONE'
    CURVE.YGF                             := 'NONE'
    CURVE.TORQUE                          := 'NONE'
    OUTLINE.SHAPE                         := 'NONE'
    SHAPE.CENTER                          := ( 0.0, 0.0 )
    ANGULAR.UNITS                         := 'DEGREES'
    FLEXIBLE                              := 'FALSE'
    SUPERELEMENT                          := 'FALSE'
UP
CREATE BODY
    NAME                                  := 'DAMPER2'
    CENTER.OF.GRAVITY                     := ( 2.0, -.75 )
    PHI                                   := '0.0'
    FIXED.TO.GROUND                       := 'FALSE'
    MASS                                  := '1.0'
    INERTIA                               := '1.0'
    XG.FORCE                              := '0.0'
    YG.FORCE                              := '0.0'
    TORQUE.CONSTANT                       := '0.0'
    CURVE.XGF                             := 'NONE'
    CURVE.YGF                             := 'NONE'
    CURVE.TORQUE                          := 'NONE'
    OUTLINE.SHAPE                         := 'NONE'
    SHAPE.CENTER                          := ( 0.0, 0.0 )
    ANGULAR.UNITS                         := 'DEGREES'
    FLEXIBLE                              := 'FALSE'
    SUPERELEMENT                          := 'FALSE'
UP
CREATE POINT.OF.INTEREST
    NAME                                  := 'P1CON'
    BODY.NAME                             := 'CONNECTOR'
    P.ON.BODY                             := ( 0.0, 0.0 )
    NODE                                  := '0'
UP
CREATE CURVE
    NAME                                  := 'CURVE1'
    TYPE.DATA                             := 'PAIRED.XY'
    SLOPE.LEFT                            := '0.0'
    SLOPE.RIGHT                           := '0.0'
    SCALE.X                               := '1.0'
    SCALE.Y                               := '1.0'
    START.X                               := '0.0'
    INCREMENT.X                           := '0.0'
    INTERPOLATION                         := 'LINEAR'
    DATA
      0.0000000000E+00   83.17000000    0.5000000000E-01   91.50000000
      0.1000000000       99.83000000    0.1500000000       108.1600000
      0.2000000000       116.4900000    0.2500000000       124.8200000
```

```
     0.3000000000     133.1500000     0.3500000000     141.4800000
     0.4000000000     149.8100000     0.4500000000     158.1400000
     0.5000000000     166.4700000     0.5500000000     158.1400000
     0.6000000000     149.8100000     0.6500000000     141.4800000
     0.7000000000     133.1500000     0.7500000000     124.8200000
     0.8000000000     116.4900000     0.8500000000     108.1600000
     0.9000000000     99.83000000     0.9500000000     91.50000000
      1.000000000     83.17000000
   ENDDATA
UP
```

Appendix D. EVA and Crew Station

D.1 Scientific Tools and Equipment

The followinNASA reports on scientific tools and equipment were referenced:

1)NASA MISSION REPORT: APOLLO-12

2)NASA FACT SHEET: LRV PERFORMANCE ON APOLLO 14 - 17 MISSIONS

3)NASA REPORT: APOLLO-12 SURFACE SURVEY AND SAMPLING, PP.3-20

4)ASTRONAUT IRWIN WITH ROVER AT APOLLO 15 LANDING SITE

The LRV aft pallet assembly is the structure which the tool carrier and other tools outside the carrier attach to. the four pallet pins seat in pallet support post holes, top and bottom, and the lower lett pallet ear lies against the LRV latch backplate. In this way, the pallet is restrained in three directions. Note that the backplate can be directly bolted to the bottom aft of the third cart and the pallet can be attached to the support post directly behind the starboard side of the third cart.

An option for the placement of the pallet assembly would be to place slots in the starboard and port sides of the third cart and slide the pallet assembly down. Then the pallet can still be latched when placed on the floor of the cart. This however can pose a problem in two areas: 1)the removal of the pallet is quite tedious needing a mounting device or elevating men atop the pallet, and 2)the starboard and port sides must be made a certain thickness as to cut suitable size dado joints for the insertion.

In the former case, the dimensions of the pallet will be 0.3m (1ft) thick by 1.8m (6ft) wide (the total width of the third cart) and no higher than 2.3m (7.5 ft) from the ground so the scientists can reach the top of the pallet.

In the latter case the width is 1.8m (6 ft) minus the thicknesses of the two sides plus the depth of cut of the dados in the starboard and port sides.

LRV STOWAGE ZONE CODE	PART NOMENCLATURE
A1	LRV AFT PALLET ASSY
A2	LUNAR HAND TOOL CARRIER
A4	PENETROMETER ASSY, SELF RECORDING
A5	BRUSH, LUNAR DUST
A6	BAGS, EXTRA SAMPLE COLLECTION
A6	SAMPLE COLLECTION BAGS
A6	SAMPLE RETURN BAG
A7	TONGS (32 INCHES)
A9	HAMMER
A10	20 DOCUMENTED SAMPLE BAG DISPENSER
A11	CORE TUBE CAP DISPENSER ASSY
A12	ADJUSTABLE SAMPLING SCOOP
A13	GNOMON
A14	LUNAR PORTABLE MAGNETOMETER

LRV STOWAGE ZONE CODE	PART NOMENCLATURE
A15	DRILL STRING VISE
A16	LUNAR SAMPLING RAKE
A17	DRIVE TUBE TOOL ASSY
B1	MAGAZINE, 16MM DAC
B2	MAGAZINE, 70MM L.S.HASSELBLAD
C2	DRILL ASSY, APOLLO L.S.
C3	BORE/CORE STEM CONTAINER ASSY
-	BORE STEM, LOWER
-	BORE STEM, UPPER
-	CORE STEM, LOWER
-	CORE STEM, UPPER
-	BORE/CORE STEM STOWAGE CONTAINER
-	BORE/CORE STEM STOWAGE COVER

Appendix E. Navigation and Communication

E.1 Data Communications

```
.dataseg

COUNT DW <12msec/(32)(clock cycle)>
SMCT DW 7
START DB <Associated with hardware>
START2 DB <Associated with hardware>
COUNT1 DW <1msec/(32)(clock cycle)>

.codeseg

MOV DX,0FFF9H ;Access input port
MOV BX,0 ;Initiate the data received count

;Actually, BX can point to index

WAITS: IN AL,DX ;Check input port for start bit
CMP AL,START
JMZ WAITS

NEXT: MOV CX,COUNT ;Delay to center bit (count intialized in datasec)
DLY1:  DEC CX
JNZ DLY1

MOV CX,SMCT ;Initate the sample number

SPLE: IN AL,DX ;Sample the data
ADD INDEX[BX],AL;Store sum
MOV DI,COUNT1 ;Delay for next sample
DLY2:  DEC DI
JNZ DLY2

LOOP SPLE ;Do till the sample number is completed
;(Averaging will be covered in another routine)

WAIT2:  IN AL,DX ;Wait for next start bit
CMP AL,START2 ;To be defined
JNZ WAIT2

INC BX ;Access next float address
CMP BX,7 ;Repeat for next sample
JNZ NEXT ;Sample next data input

ENDP
END
```

Appendix F. Heat Rejection and Protection

F.1 Heat Rejection

F.1.1 Heat Sink Temperature

Equivalent heat sink temperature is the temperature that a body would see as a result of its surroundings. For the radiator/storage system, the heat sink temperature was calculated by taking into effect the surrounding temperature contributions from the solar shield, the sides of the vehicle. The bottom of the vehicle did not come into effect for the temperature, as the bottom of the vehicle will be thermally insulated.

F.1.1.1 Temperature of Solar Shield

In calculating the temperature effect of the solar shield the sun was assumed to deliver a flux of 1360 W/m^2 to all objects on the surface of the moon when the sun is directly overhead the object. The following calculation determined the temperature of the solar shield on top of the vehicle due to the flux from the sun and assuming that the reflection of the solar shield is .9.

$$\alpha_{shield} G_{sun} = \epsilon\sigma({T_{shield}}^4 - {T_{sky}}^4)$$

α_{shield} = absorptivity of shield
G_{sun} = solar flux delivered to object
ϵ = emissivity of shield
σ = constant=5.67×10^{-8} W/(K^4·m^2)
T_{shield} = temperature of solar shield in K
T_{sky} = temperature of surrounding sky in K

$$.10(1360 \text{ W/m}^2) = (.9)(5.67 \times 10^{-8} \text{ W/(K}^4\cdot\text{m}^2))[{T_{shield}}^4 - 3^4]$$

$$T_{shield} = 227K$$

F.1.1.2 Temperature of the Surface of the Moon

The temperature on the surface of the moon is also calculated as a function of the sun's solar radiation flux. The following calculation determines the temperature of the surface of the moon assuming an absorptivity of .9 for the lunar surface.

$$\alpha_{moon} G_{sun} = \epsilon\sigma({T_{moon}}^4 - {T_{sky}}^4)$$

α_{moon} = absorptivity of moon
G_{sun} = solar flux delivered to object
ϵ = emissivity of moon
σ = constant= 5.67×10^{-8} W/(K^4·m^2
T_{moon} = temperature of moon in K
T_{sky} = temperature of surrounding sky in K

$$(.9)(1360 \text{ W/m}^2) = (1)(5.67 \times 10^{-8} \text{ W/(K}^4\cdot\text{m}^2)({T_{moon}}^4 - 3^4)$$

$$T_{moon} = 383K$$

F.1.1.3 Temperature of the Vehicle (Vertical Sides)

The temperature on the vehicle sides are a function of the flux emitting from the surface of the moon. Since the sun is directly overhead, it will contribute no solar flux to the vertical panels. The moon is a blackbody which means the emissivity is 1.

$$\alpha_{\text{vehicle}} G_{\text{moon}} = \epsilon\sigma({T_{\text{moon}}}^4 - {T_{\text{vehicle}}}^4)$$

$G_s = \epsilon\sigma {T_{\text{moon}}}^4$
$\alpha_{\text{vehicle}} =$ absorptivity of vehicle
$G_{\text{moon}} =$ flux delivered to object by the surface of the moon
$\epsilon =$ emissivity of vehicle
$\sigma =$ constant $= 5.67 \times 10^{-8}$ W/(K^4·m^2)
$T_{\text{vehicle}} =$ temperature of vehicle in K
$T_{\text{moon}} =$ temperature of lunar surface in K

$$G_s = (1)(5.67 \times 10^{-8}\ \text{W/(K}^4\cdot\text{m}^2))(383^4) = 1220\ \text{W/m}^2$$

$$(.12)(1220\ \text{W/m}^2) = (.06)(5.67 \times 10^{-8}\ \text{W/(K}^4\cdot\text{m}^2))(383^4 - {T_{\text{vehicle}}}^4)$$

$$T_{\text{vehicle}} = 370\ \text{K}$$

F.1.1.4 Equivelent Heat Sink Temperature

The equivalent sink temperature is a function of all of the surrounding bodies. Since each body represents a different area, the temperature term of each body is multiplied by the ratio of its area to the total surrounding area. An emissivity of .06 is assumed for the surrounding surfaces. The heat transfer rate is assumed to be 0.0 between the body at sink temperature and the surrounding temperature, in other words, the bodies are in equilibrium.

$$\begin{aligned} q'' = \sigma((\epsilon_1)(\frac{A_1}{A_t})({T_{\text{surface1}}}^4 - {T_{\text{sink}}}^4) + ((\epsilon_2)(\frac{A_2}{A_t})({T_{\text{surface2}}}^4 - {T_{\text{sink}}}^4) \\ + ((\epsilon_3)(\frac{A_3}{A_t})({T_{\text{surface3}}}^4 - {T_{\text{sink}}}^4) + ((\epsilon_4)(\frac{A_4}{A_t})({T_{\text{surface4}}}^4 - {T_{\text{sink}}}^4) \\ + ((\epsilon_5)(\frac{A_5}{A_t})({T_{\text{surface5}}}^4 - {T_{\text{sink}}}^4) \end{aligned}$$

$q'' =$ heat transfer rate $= 0.0$ for equilibrium
$\sigma =$ constant $= 5.67 \times 10^{-8}$ W/(K^4·m^2
$\epsilon_1 =$ emissivity of surface 1 = solar shield
$\epsilon_2 =$ emissivity of surface 2 = 2.74 m × 1.29 m vertical side
$\epsilon_3 =$ emissivity of surface 3 = 2.74 m × 1.29 m vertical side
$\epsilon_4 =$ emissivity of surface 4 = 1.83 m × 1.29 m vertical side
$\epsilon_5 =$ emissivity of surface 5 = 1.83 m × 1.29 m vertical side
$A_1/A_t =$ area of surface 1 over A_t = solar shield
$A_2/A_t =$ area of surface 2 over A_t = 2.74 m × 1.29 m vertical side
$A_3/A_t =$ area of surface 3 over A_t = 2.74 m × 1.29 m vertical side
$A_4/A_t =$ area of surface 4 over A_t = 1.83 m × 1.29 m vertical side
$A_5/A_t =$ area of surface 5 over A_t = 1.83 m × 1.29 m vertical side

$T_{surface1}$ = temperature of surface 1
$T_{surface2}$ = temperature of surface 2
$T_{surface3}$ = temperature of surface 3
$T_{surface4}$ = temperature of surface 4
$T_{surface5}$ = temperature of surface 5

$$0.0 = (5.67 \times 10^{-8} \text{ W}/(\text{K}^4 \cdot \text{m}^2))((.06)(5.0169 \text{ m}^2)((227K)^4 - T_{sink}{}^4) + (.06)(2.3628 \text{ m}^2)(2)((227K)^4 - T_{sink}{}^4) + (.06)(3.542m^2)(2)((227K)^4 - T_{sink}{}^4)$$

$$T_{sink} = 343.6 \text{ K}$$

F.1.2 Calculation of Mass of Solar Shield

The mass of the solar shield is calculated by assuming a shield of 2024 Aluminum which has a thickness of .005m and a surface area which is the same as the cart (5.0169 m^2).

$$(\text{density of material})(\text{thickness})(\text{surface area}) = \text{mass}$$

Assuming aluminum with a density of 2.7115 kg/m^3,

$$(2.7115 \text{ kg/m}^3)(.005 \text{ m})(5.0169 \text{ m}^2) = .0680 \text{ kg}$$

F.1.3 Storage System

F.1.3.1 Calculate the Mass of the Storage Section

The mass of potassium needed to store 4 kWhr of energy using latent heat storage is shown below. The following are the constants for the storage system [25].

m = mass of potassium needed to store Q
Q = amount of energy to be stored = 4 kWhr
c_p = specific heat = 2.09×10^{-4} kWhr/(kJ·K)
L = latent heat of liquid = 1.686×10^{-2} kWhr/kg
T_{max} = maximum temperature of storage system = 96° C
T_{melt} = melting temperature of potassium = 63.3° C
T_{min} = minimum temperature of storage system =22° C
ρ = density of potassium = 763 kg/m^3
V = volume of potassium

$$\begin{aligned} Q &= Q_{melt} + Q_{latent} + Q_{aftermelting} \\ &= mc_p\Delta T + mL + mc_p\Delta T \\ &= mc_p[T_{melt} - T_{min}] + mL + mc_p[T_{max} - T_{melt}] \\ m &= \frac{Q}{c_p[T_{melt} - T_{min}] + L + c_p[T_{max} - T_{melt}]} \\ &= 126.5 \text{ kg} \end{aligned}$$

Calculate the volume of potassium needed.

$$V = \frac{m}{\rho}$$
$$= \frac{126.5kg}{763\frac{kg}{m^3}}$$
$$= .17 \text{ m}^3$$

Assuming a perfect cube, each side will be .54 m.

If the amount of heat to be stored is 2.96 kWhr,

$Q =$ 2.96 kWhr
$m =$ 92.7 kg
$V =$ 0.12 m^3

Assuming a perfect cube, each side will be .49 m (1.62 ft).

F.1.3.2 Time to Cool the Storage System

Knowing the volume of potassium to store a certain amount of energy, it is necessary to determine the amount of time it will take to cool the storage system from 96°C to 23°C [36].

$T_I =$ initial temperature of storage system = 96°C
$T_F =$ final temperature of storage system = 23°C
$A =$ surface area of storage system = 5 × $.54\text{m}^2$ = 1.46 m^2
$V =$ volume of storage system = .17 m^3
$T_2 =$ temperature of environment = 22°C
$\epsilon =$ emissivity of storage system = .9
$\tau =$ time to cool storage system
$\sigma =$ Stefan-Boltzmann constant = $5.67 \times 10^{-8}\text{W}/(\text{K}^4\cdot\text{m}^2)$

$$V\rho c_p \frac{dT_1}{\tau} = A\sigma\epsilon[T_1^4(\tau) - T_2^4]$$

$$-\int_{T_I}^{T_F} \frac{dT_1}{T_1^4 - T_2^4} = \frac{A\epsilon\sigma}{Vc_p\rho}\int_0^{\tau} d\tau$$

$$\left(\frac{1}{4T_2^3}\ln\left|\frac{T_1 + T_2}{T_1 - T_2}\right| + \frac{1}{2T_2^3}\arctan\frac{T_1}{T_2}\right)\Bigg|_{T_I}^{T_F} = \frac{A\epsilon\sigma\tau}{Vc_p\rho}$$

$$\tau = \frac{Vc_p\rho}{A\epsilon\sigma}\left[\frac{1}{4T_2^3}\ln\left|\frac{(T_F + T_2)(T_I + T_2)}{(T_F - T_2)(T_I + T_2)}\right| + \frac{1}{2T_2^3}(\arctan\frac{T_F}{T_2} - \arctan\frac{T_I}{T_2}\right]$$

$$\tau = 22.6 \text{ hours}$$

If only 2.96 kWhr is being stored,

$A =$ 5 × $.49^2$ = 1.20 m
$V =$ .12 m^3
$\tau =$ 19.0 hours

F.1.4 Radiator Sizing

F.1.4.1 Calculate Heat Rejected by Radiator at Lunar Night

The amount of heat that needs to be rejected at night is 400 W. In sizing the radiator for night use, assume that the tubes are .5 in (.0127 m) in diameter. The length of the fin is 3.75 in (.09525 m).

$Q_f =$ heat radiated by fin per tube
$Q_{ftotal} =$ total heat rejected by fins

$Q_t =$ heat radiated by a tube
$Q_{ttotal} =$ total heat radiated by all tubes
$Q =$ total heat radiated by radiator
$L =$ length of fin $= .09525$ m
$\epsilon =$ emissivity of radiator $= .9$
$\sigma =$ Stefan-Boltzmann constant
$\eta =$ fin effectiveness (from Fig 6-9; p. 183) [37]
$N_c =$ conductance parameter
$T_b =$ temperature at base of fin $= 96°$C $= 369$K
$T^* =$ heat sink temperature $= -268°$C $= 4$K
$k =$ thermal conductivity of titanium $= 21.9$ W/(m·K) [18]
$t =$ thickness of fin $= .075$ in (.0019m)
$l =$ length of radiator $= .914$ m

Calculate the conductance parameter and the ratio of T_b to T*.

$$\frac{T^*}{T_b} = .01$$

$$N_c = \frac{\epsilon\sigma T_b^3 L^2}{kt}$$

$$N_c = .6$$

$$\eta = \frac{q_f}{q_{ideal}}$$

$$q_{ideal} = L\epsilon\sigma[T_b^4 - T^{*4}]$$

$$q_f = \eta L\epsilon\sigma[T_b^4 - T^{*4}]$$

$$q_f = 52.75 \text{ W/m}$$

$$Q_f = q_f \times l$$

$$Q_f = 52.75 \text{ W per fin}$$

$$Q_{ftotal} = 52.75 \text{ W} \times 8 = 420.4 \text{ W}$$

Calculate heat dissipated by 4 tubes.

$$Q_t = \epsilon\sigma \mathrm{A}[T_b^4 - T^{*4}]$$

$$A = \pi \times r \times l = \pi \times .0064 \times .91 = 1.83 \text{ m}^2$$

$$Q_t = 17.7 \text{ W}$$

$$Q_{ttotal} = 17.7 \text{ W} \times 4 = 70.8 \text{ W}$$

$$Q_{total} = 420.4 \text{ W} + 70.8 \text{ W} = 491.2 \text{ W}$$

F.1.4.2 Calculate Heat Rejected by Radiator During Lunar Day

Calculate how much heat will be rejected when $T^* = 343$ K.

$N_c = .58$
$q_f = 13.2$ W/m
$Q_f = 13.2$ W/m $\times$ .91 m $= 24$ W
$Q_{ftotal} = 24$ W $\times$ 8 $= 96$ W
$Q_t = 4.38$ W

$Q_{ttotal} = 4.36 \text{ W} \times 4 = 17.44 \text{ W}$
$Q_{total} = 96 \text{ W} + 26.3 \text{ W} = 113.44 \text{ W}$

Therefore 409 W - 113.44 W = 296 W has to be stored.

F.1.4.3 *Calculate Thickness of Radiator Tubes*

$t =$ thickness of radiator tubes = .0019 m
$n =$ factor of safety = 1.5
$P =$ pressure of water in tubes = 20 psi[25] = 1.03×10^5 Pa
$D_i =$ inside diameter of tube = .5 in = .0127 m
$S_y =$ yield stress of titanium = 45 kpsi = 3.1 $\times 10^8$ Pa [25]

$$\sigma \frac{= nPD_i}{2t}$$

$$\sigma = 5.16 \times 10^5 \text{ Pa}$$

Since $S_y > \sigma$, .075 in (.0019 m) will be an adequate thickness. Since the thickness of the armor has to be at least .0018 m, a thickness of .0019 m will be sufficient.

Tube outer diameter = .0127 + 2(.0019 m) = .0165 m (.65 in).

Therefore the tube outer diameter will be .0165 m (.65 in).

The total width of the radiator will be 1.24 m (4.08 ft).

F.1.4.4 *Calculate Weight of the Radiator*

$m_f =$ mass of the fins
$m_t =$ mass of the tubes
$\rho =$ density of titanium = 4500 kg/m^3
$l =$ length of radiator = .91 m
$t =$ thickness of fins = .0038 m
$n =$ number of fins = 12
$N =$ number of tubes = 6 (for redundancy)
$L =$ length of fins = .095 m
$D_o =$ outside diameter of tubes = .0165 m
$D_i =$ inside diameter of tubes = .0127 m

$$m_f = l\,t\,L\,n\,\rho$$

$$m_f = 17.7 \text{ kg}$$

$$m_t = \frac{\pi}{4}(D_o^2 - D_i^2)\,l\,N\,\rho$$

$$m_t = 2.16 \text{ kg}$$

Total weight of radiator = 20.0kg

F.1.4.5 *Calculate Bending Moment of Radiator*

This calculation determines whether the radiator can hold its own weight and whether it will sag. Assume the radiator is supported at both ends.

Bending moment along width

$$M_{\max} = (20.6kg)(9.81\ \mathrm{m/s^2})(.63m) = 127.3\ \mathrm{Nm}$$
$$y = .0019m$$
$$I = \frac{1}{12}\ \mathrm{bh^3} = \frac{1}{12}(.91\mathrm{m})(.0038\mathrm{m})^3 = 4.16 \times 10^{-9}\mathrm{m^4}$$
$$n = 1.5$$
$$\sigma = \frac{My}{I}$$
$$\sigma = 5.814 \times 10^7 Pa$$
$$S_y > n\sigma = 8.72 \times 10^7 Pa$$

Since $S_y > 8.72$ X 10^7 Pa, the radiator will hold its own weight.

Bending moment along length

$$M_{\max} = (20.6kg)(9.81\ \mathrm{m/s^2})(.457m) = 92.5Nm$$
$$y = .0019m$$
$$I = \frac{1}{12}\mathrm{bh^3} = \frac{1}{12}(1.26m)(.0038m)^3 = 5.76 \times 10^{-9}\mathrm{m^4}$$
$$n = 1.5$$
$$\sigma = \frac{My}{I}$$
$$\sigma = 3.05 \times 10^7 Pa$$
$$n\sigma = 4.57 \times 10^7 Pa$$

Since $S_y > \mathrm{n}\sigma$, the radiator will hold its own weight in this direction also.

F.1.4.6 Calculate Mass Flow Rate of Water through Tubes

Calculate the mass flow rate during a lunar night.

$q =$ heat rejected $= .6094$ kW

$\Delta T = 365°$

$c_p =$ specific heat of water $= 1.16 \times 10^{-3}$ kWhr/(kg·K)

$$q = \dot{m} c_p \Delta T$$
$$\dot{m} = .00041 \mathrm{kg/s}$$

Calculate the mass flow rate during a lunar day.

$q = .446$ kW

$\Delta T = 10°$

$$\dot{m} = .011\ \mathrm{kg/s}$$

F.2 Solar Radiation Protection

For aluminum shielding it was determined that 10 g/cm^2 is required in order not to exceed the 15 REM limit per astronaut [28] . 3.5 REMs per hour corresponds to the amount of radiation received per hour if you had a surface density of 10 g/cm^2.

$\frac{3.5 Rems}{hour} 4hour = 14 REMs$

Aluminum Shielding: Assuming a density of 2711.5 kg/m^3 for aluminum and a required shielding of 10 g/cm^2 the thickness of the blanket is calculated to be:

$\frac{100kg}{m^2} \frac{1m^3}{2711.5kg}$=.03688 m = 3.688 cm

The blanket is to be a spherical piece of fabric covering the head of radius .3810 m attached to a cylindrical body piece of radius .381 m and a height of 2.032 m.

The mass of the aluminum shielding is calculated by multiplying the volume of the shielding by the density of aluminum.

inner volume: $\frac{4}{3}\pi(.381)^3 + \pi(.381)^2 1.65 = .98413 m^3$

Outer volume is obtained by adding the thickness to the inner volume and using these new dimensions to calculate the volume.

outer volume: $\frac{4}{3}\pi(.381 + .03688)^3 + \pi(.381 + .03688)^2 1.65 = 1.21105 m^3$

total volume = 1.21105 - .98413 = .22692 m^3

mass = (.22692 m^3)$\frac{2711.5kg}{m^3}$ = 615kg

This following is the calculation for the mass of carbon fiber cloth assuming that the surface density is .68 kg/m^2. (8 g/cm^2 of carbon fiber cloth is equal to 10 g/cm^2 of aluminum)

surface area (sphere): $\pi((\frac{6\frac{4}{3}\pi(.3831)^3}{\pi})^{1/3})^2 = 1.82400 m^2$

surface area (cylinder): $2\pi(.38190)(1.65) = 3.94992 m^2$

Total surface area: 1.82400 + 3.94992 = 5.77392 m^2

weight of carbon fiber cloth: 5.7739 m^2 $\frac{.68kg}{m^2}$ = 3.927 kg

F.3 Meteroid Protection

F.3.1 Radiator Armor Thickness

The titanium radiator tubes will have an armor to protect themselves from meteoroid impact. The following are the characteristics of the meteoroid the tubes were protected against:

Meteoroid mass = m_p = 1.5 x 10$^-$8 kg

Meteoroid density = ρ_p =.5 g/cm^3

Meteoroid velocity = u_p = 20 km/s

$S_t^{1/3}$ = 3.20 (J/mm)^3 at 775 K

Titanium density = ρ_t = 4.85 g/cm^3

ρ_∞ = infinite penetration thickness

TPT = threshold penetration thickness

The equation used to determine the infinite penetration thickness was developed by Charters and Summer.

$\rho_\infty = (\frac{81}{8\pi}\frac{\rho_p}{\rho_t} m_p u_p^2)^{1/3}\frac{1}{S_t^{1/3}}$

ρ_∞ = .787 mm

TPT = 1.5ρ_∞

TPT = 1.18 mm

Therefore, each tube will be made of an extra thickness of 1.18 mm titanium to protect itself 99% of the time from penetration of a meteoroid of mass 1.5 x 10^{-8} kg or less.

F.4 Dust Protection

F.4.1 Fender and Flap Calculations

The fender and flaps are shown in Fig. 7 - Fig. 10. Calculations have to be made of the volume and mass of the fender and flaps and the feasibility of attaching the fender to the back plate and to the end of the shaft.

t = thickness of fender = .0013 m

r_i = inner radius of fender = 1.3 m

r_o = outer radius of fender = 1.3013 m

l = length of cylindrical part of fender = .3 m

h = height of the flaps = .61 m

V_s = volume of one quarter sphere

V_b = volume of square removed so it will attach to backplate

V_c = volume of cylinder

V = volume of fender

V_f = volume of one flap

ρ = density of Kevlar 49 = 1480 kg/m^3

M = mass of the fender and flaps for one wheel

Calculate the volume of the fender.

Calculate the volume of 1/4 spherical shell.

$V_s = \frac{1}{4} * \frac{4\pi}{3} * [r_o^3 - r_i^3]$

$V_s = \frac{1}{4} * \frac{4\pi}{3} * [1.3013^3 - 1.3^3]$

V_s = .0069 m^3

Since the fender is not a compete quarter sphere it has to be taken into consideration that the fender is located 10° to 170°.

$V_s = \frac{160}{180} * .0069 m^3$

V_s = .0061 m^3

Calculate the volume of the cylinder which is an extension of the hemispherical wheel. The fender will extend an extra .05 m over the wheel. The cylindrical part of the fender will also only extend from 10° to 170°.

$V_c = \frac{1}{2} * \pi * l * [r_o^2 - r_i^2]$

$V_c = \frac{1}{2} * \pi * .3 * [1.3013^2 - 1.3^2]$

V_c = .0016 m^3

$V_c = \frac{160}{180} * .0016 m^3$

V_c = .0014 m^3

Calculate the square part of the fender which has to removed so that the fender can be connected to the .31 m (1 ft) by .91 m(3 ft) plate.

Horizontal distance to be cut is (.3054 + .03 + .03)m = .3654 m. See Fig. F.1 A.

$\sin \phi = \frac{.1827}{1.8}$

$\phi = 8.08°$

$\frac{\pi}{180} * 8.08 * 1.3 = .1833m$

.1833*2 = .3666 m

This is the curved horizontal distance.

Vertical distance to be cut = .44 m. See Fig. F.1B.

$\sin \alpha = \frac{.44}{1.8}$

$\alpha = 20.72°$

$\frac{\pi}{180} * 20.72 * 1.3 = .47m$

This is the curved vertical distance.

V_b = curved horizontal distance*curved vertical distance*thickness

$V_b = .3666 * .47 * .0013 = .00022m^3$

The total volume of the fender:

$V = V_s + V_c - V_b$

$V = .0061 + .0014 - .00022$

V = .0073 m^3

Calculate the volume of the flaps.

$V_f = \theta * r * h * t$

$V_f = [90 - 20.72] * \frac{\pi}{180} * 1.3 * .61 * .0013$

$V_f = .0013m^3$

Calculate total volume of fender and flaps.

$V_{\text{total}} = V + V_f$

$V_{\text{total}} = .0073 + 2 * .0013$

$V_{\text{total}} = .0099$ m^3

Calculate the mass of the fender and flaps for one wheel.

$M = \rho * V_{\text{total}}$

$M = 1480 \frac{kg}{m^3} * .0099m^3$

M = 14.65 kg

Calculate the total mass for all six wheels.

$M_{\text{total}} = 6 * M$

$M_{\text{total}} = 87.9kg$

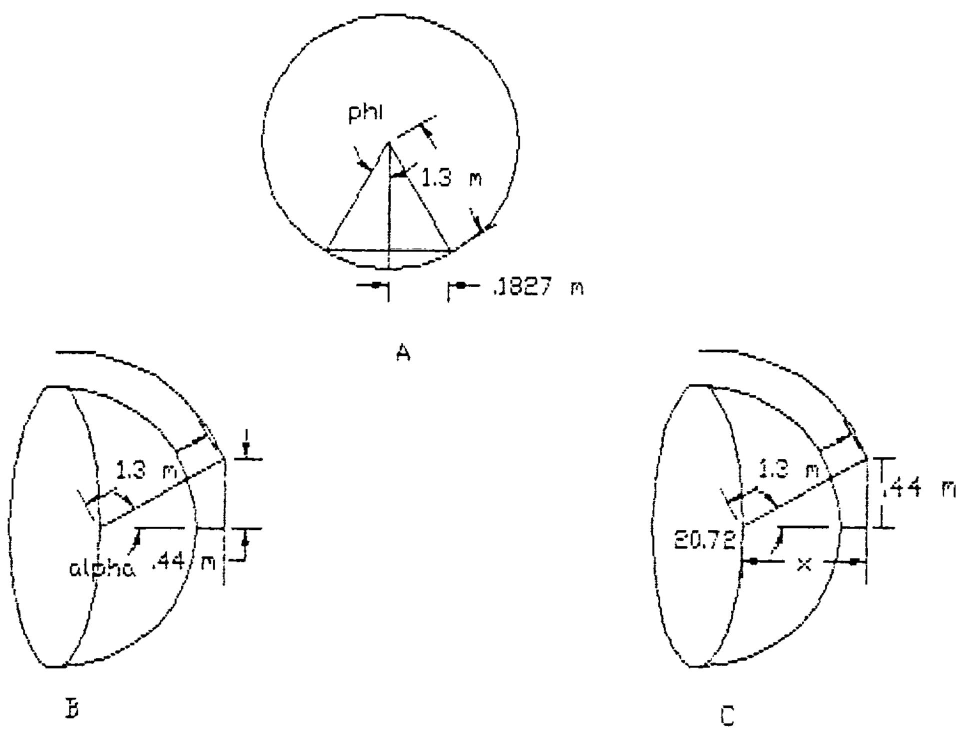

Figure F.1. Dust protection appendix drawing.

Calculate to make sure that the fender can attach to the plate and still remain .15m from the wheel. See Fig. F.1C.

The length from the center of the wheel to the plate.

x = 1.15 m + .076 m = 1.22 m

Using trigonometry to determine what the length will be with the fender attached.

$x = \cos\alpha * r_i$

x = cos(20.72) * 1.3

x = 1.226 m

Therefore the fender will be able to be attached and will remain .15 m from the wheel.

Calculate the diameter of the Aluminum 2024 T6 rods. Assume the weight of the fender and flaps acts in the center of wheel.

E = modulus of elasticity = 71 GPa

l = length of rod = 1.3 m

I = moment of inertia = $\frac{1}{4} * \pi * r^4$

ρ = density of Aluminum 2024 T6 = 2700 kg/m^3

Calculate the weight on the rod.

Weight = 16.7kg* 9.81m/s^2 = 143.7 N

Force = P_{cr} = 143.7/cos(45) = 203.2 N

Calculate the diameter by using bending in columns [17].

$P_{cr} = \frac{\pi^2 * E * I}{4 * l^2}$

$P_{cr} = \frac{\pi^3 * E * r^4}{16 * l^2}$

$r = \sqrt[4]{\frac{16 * l^2 * P_{cr}}{E * \pi^3}}$

$r = \sqrt[4]{\frac{16 * 1.3^2 * 203.2}{71E9 * \pi^3}}$

r = .007 m = .003 ft = .28 in

d = .55 in

Calculate the mass of the supports.

$V = \pi * r^2 * l$

$V = \pi * .007^2 * 1.3 = .0002m^3$

$M = V * \rho = .0002 * 2700 = .54kg/m^3$

Calculate total mass of supports for all six wheels.

$M_{total} = 12 * M = 6.5kg$

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